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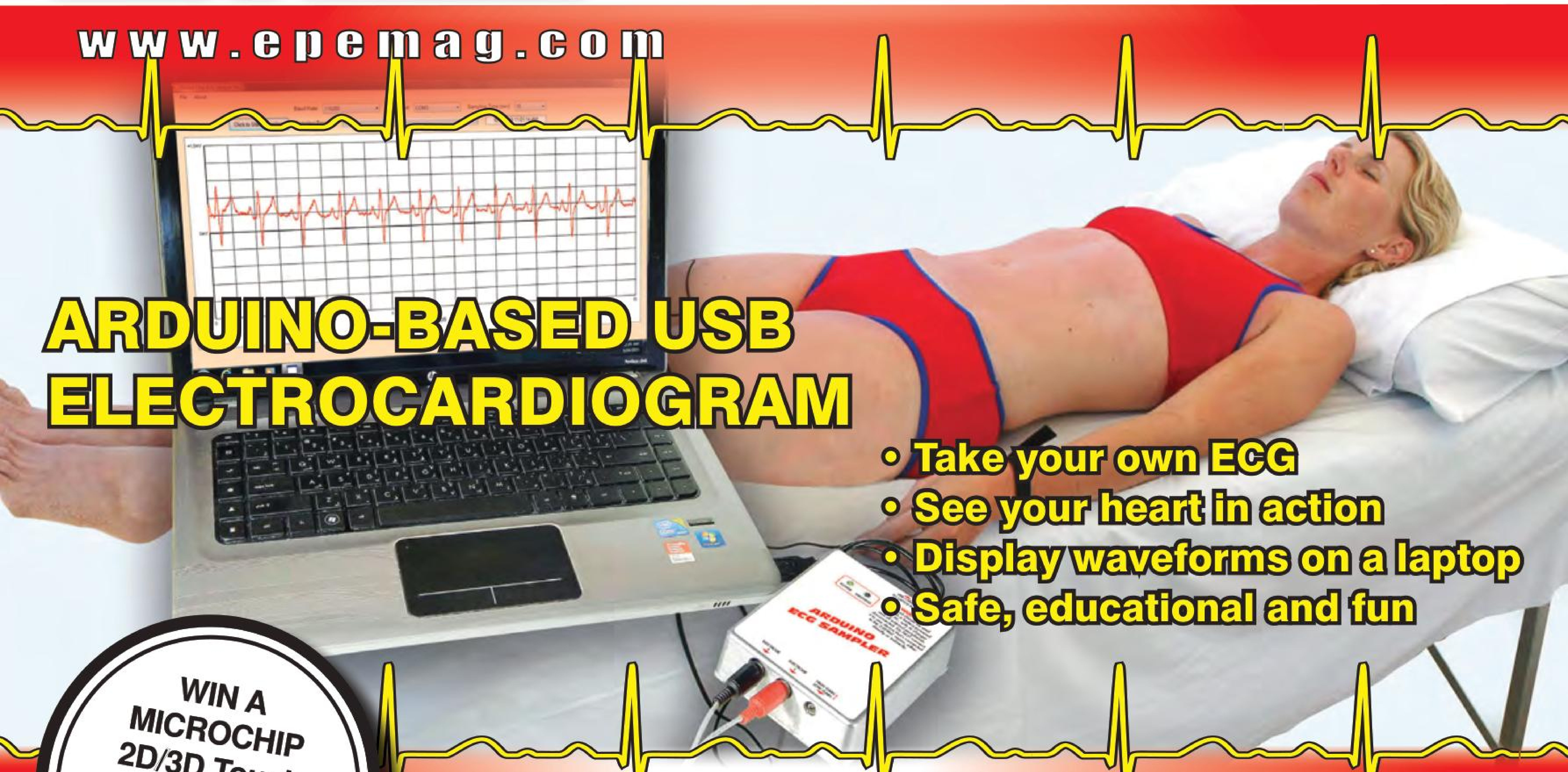

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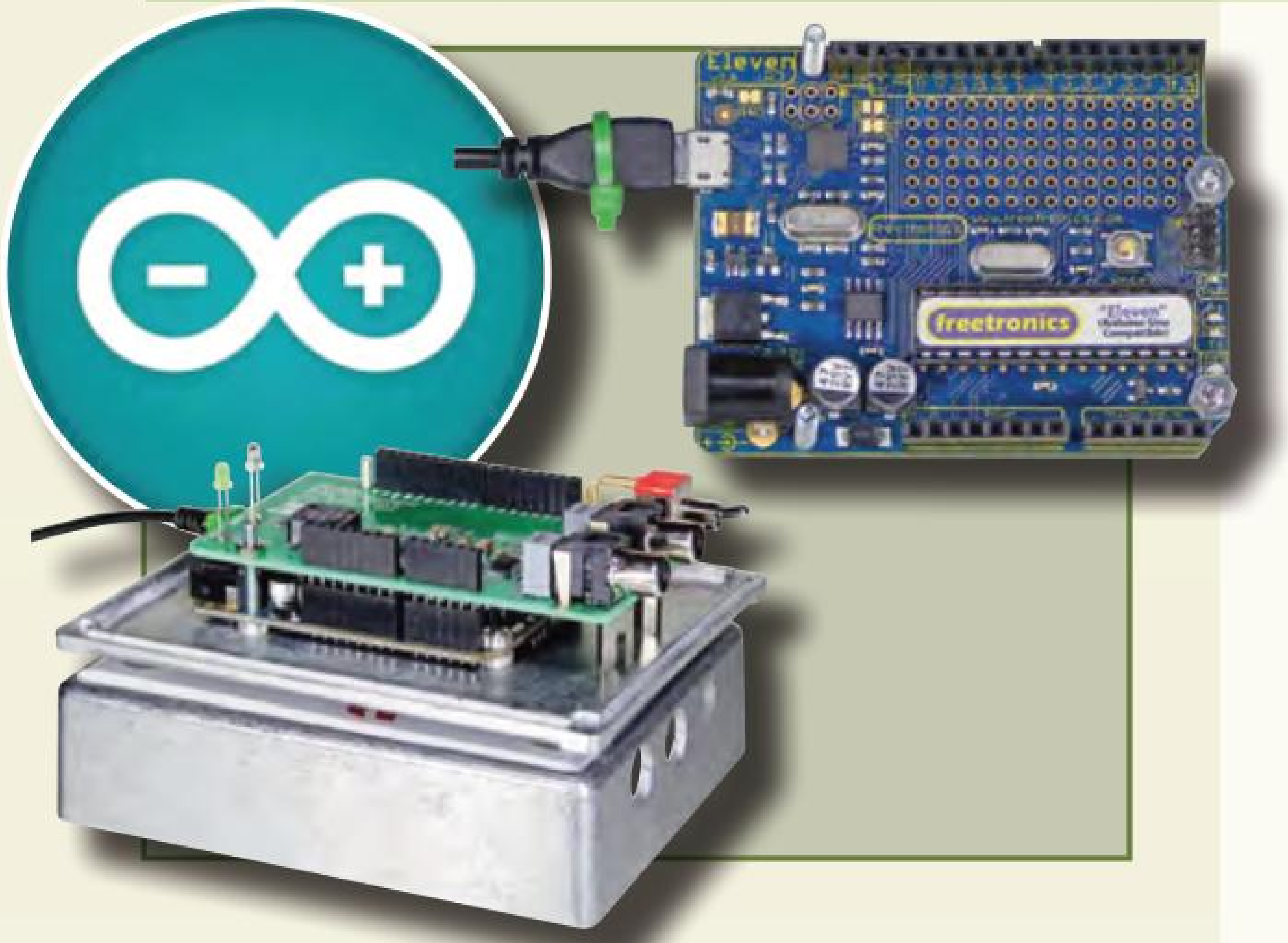

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Our November 2016 issue will be published on Thursday 6th October 2016, see page 72 for details.

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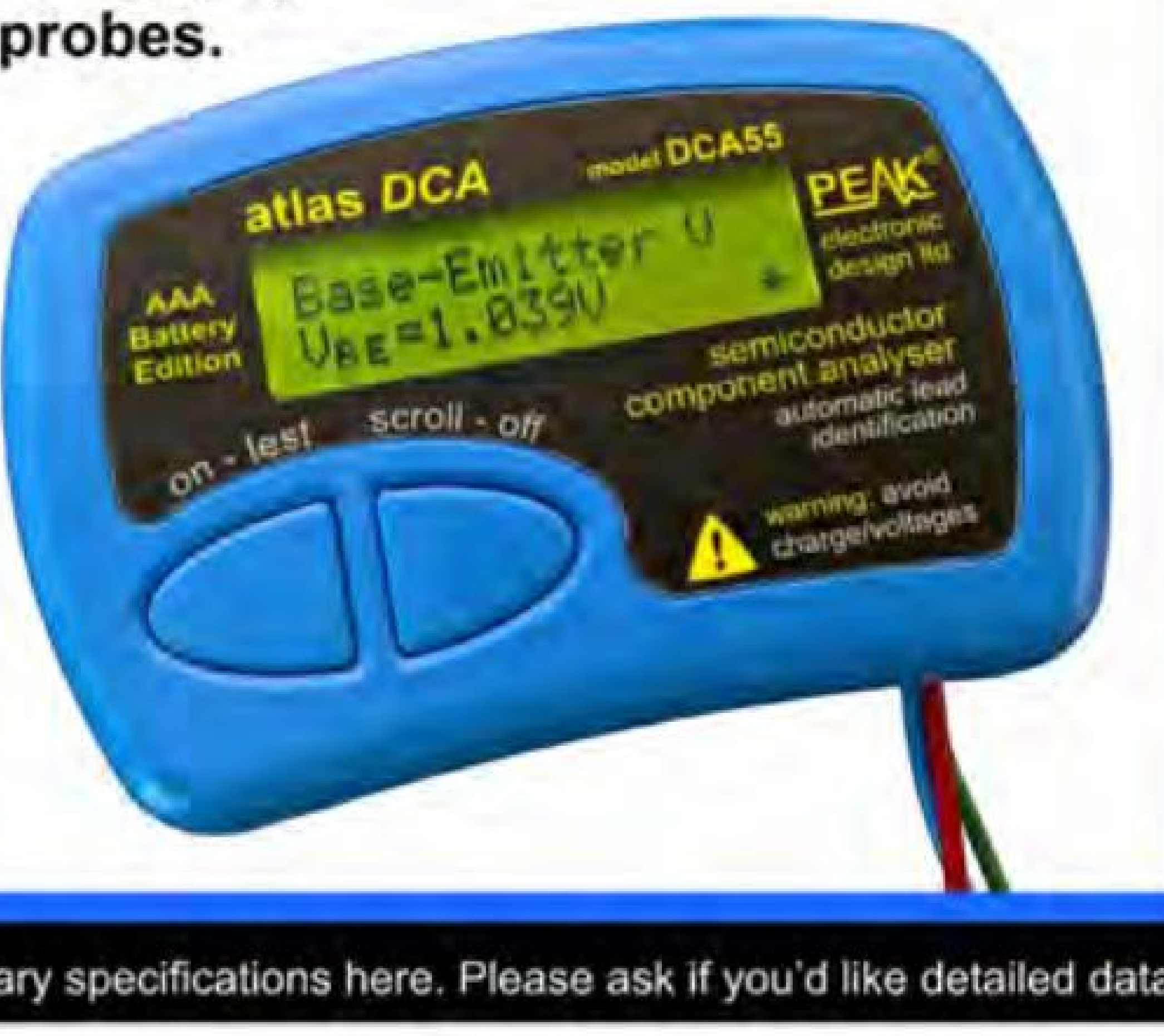
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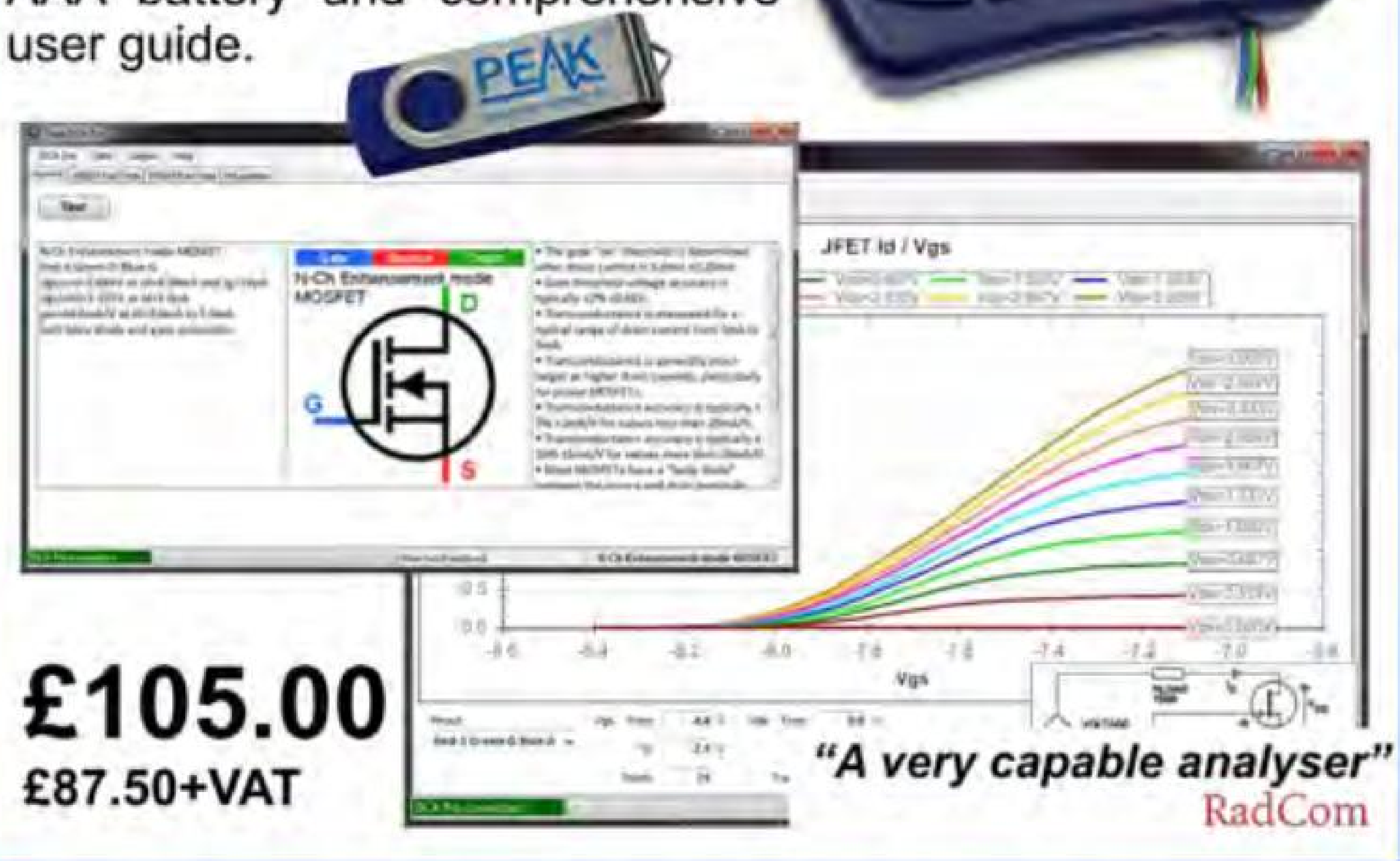
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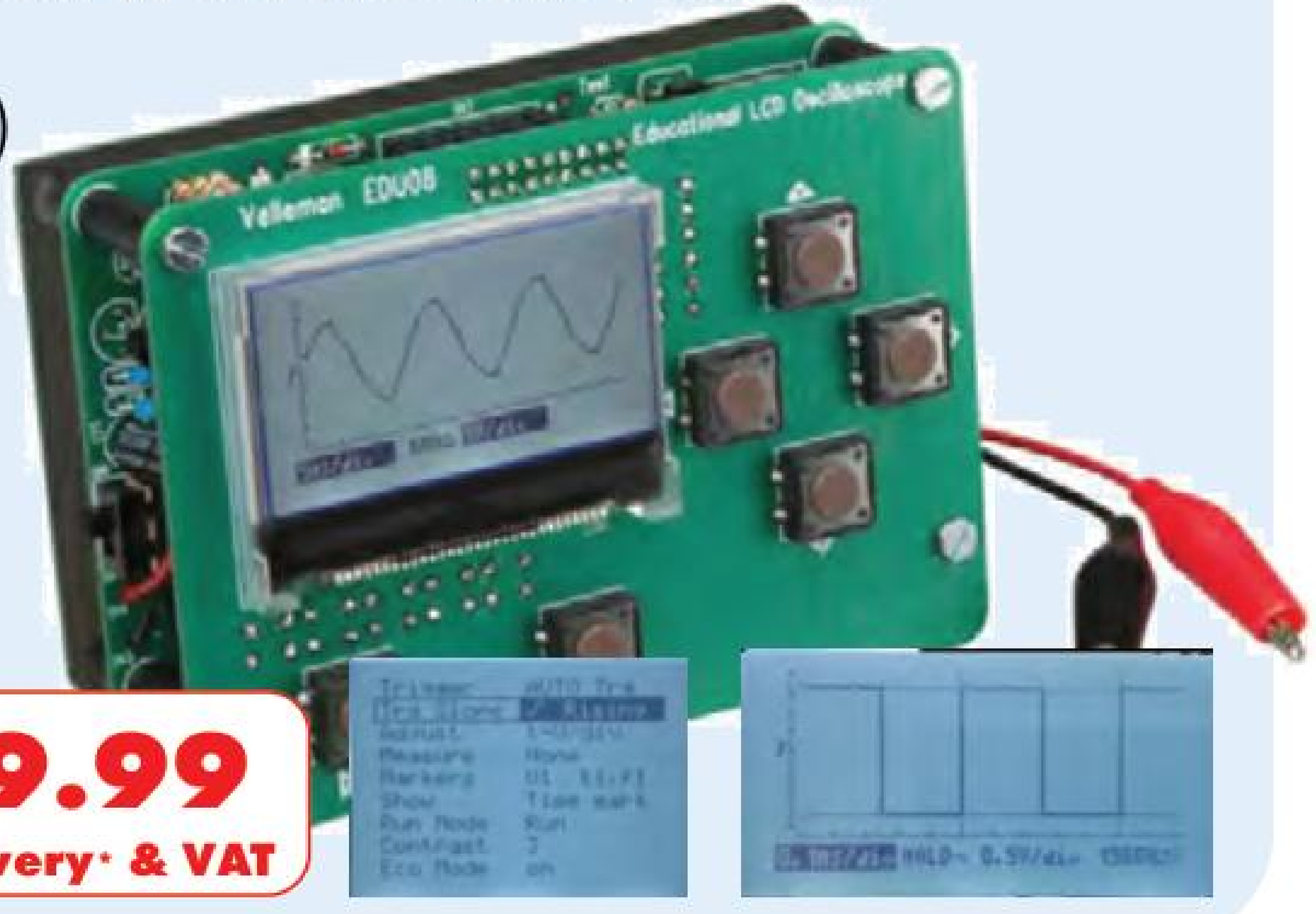

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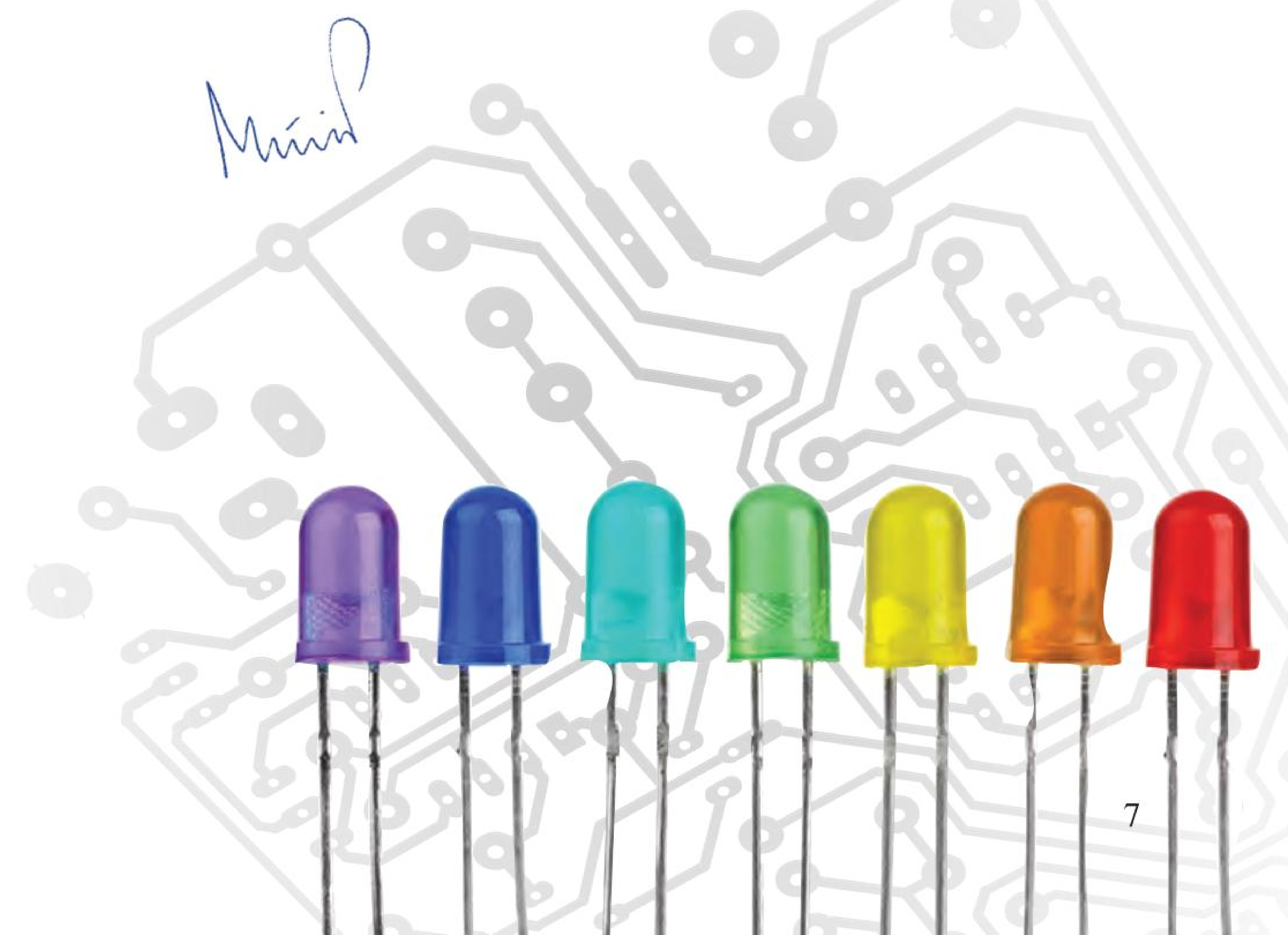
Power of the Arduino

Recently, I was browsing through my collection of *EPE* magazines and was struck by the rise in project sophistication over that last couple of decades. Without question, the standout change has been the addition of embedded intelligence, something we now almost take for granted.

Alongside this innovation has been an equally impressive change in how this intelligence is added. There are so many powerful, flexible, cheap and user-friendly microcontroller/miniature computer systems available today that home constructors are really spoilt for choice. Long gone are the days when a 'smart' project meant hooking up a PCB to a bulky PC via complex interfaces with all the lack of portability and restrictive power requirements which that involved. Of course, 'back in the day' using a computer to control a project was an exciting and rewarding route to project expansion, but the phenomenal rise of microcontrollers, especially the PIC has meant that fast, low-power and ultra-compact intelligence is now easily added to almost any project. Indeed, we have almost reached the point where not adding digital control is a design point that needs discussing and justifying.

It is almost impossible to adequately cover all digital control options and for a long time *EPE* concentrated on PICs, which offered the best balance of power, flexibility and value for money, albeit with a degree of extra design challenge. We like to think we know what our readers want and saw the 'design challenge' as a bonus, not a hindrance.

We still view PICs as the gold standard, but the arrival of other high quality control options, such as Raspberry Pi enabled us to widen our coverage. We have always been of the opinion that is its better to cover a few control options in depth, rather than many superficially, and inevitably this meant missing out on a few popular alternatives. Top of this list was the Arduino, and while we may have been a little late in using this flexible and popular system, we are now making up for lost time with Mike Tooley's current *Teach-In* series. This means that we can now bring you some excellent Arduino projects and I hope you enjoy reading this month's *Arduino-based USB Electrocardiogram* project, which really shows how much can be achieved with this highly accessibly system. I'm sure we will have many more projects built around the Arduino platform and I hope you are inspired to design your own.



NEWS

A roundup of the latest Everyday News
from the world of
electronics

HDR+: a new word for a new idea – report *by Barry Fox*

Literally millions of people now own 4k UHD TV sets and are waiting for 4k broadcasts. But there won't be any on terrestrial services like Freeview for the foreseeable future because there is no spare bandwidth.

Enter HDR+

So use 'HDR+', Matthew Goldman, SVP Technology, Ericsson, told the SES/Astra Ultra HD conference held in London recently.

'HDR+ gives the best bang for your bandwidth bits and is the way to make images pop without needing much extra bandwidth', he told the industry audience. 'Broadcast in 1080p HD and 10 bits with wide colour gamut and high dynamic range, and leave it to the upscaling circuitry built into UHD sets to put 4k pictures on the screen.

Less is more

'Whereas 2160p broadcasts need 250% more bandwidth, 1080p HDR+ adds only between 0 and 20%, depending on the HDR system. Upscaling in the set to 4k 2160p will give something much better than you can offer now.

'Our (Ericsson's) consumer tests show that better contrast gives the effect of higher resolution – if you show people 2160p with standard dynamic range and 1080p with high dynamic range they prefer 1080p' Goldman explained. '1080p viewing should be from a distance of three picture heights and 4k should be viewed from 1.5 picture heights. If you are not close enough you are watching HD. You don't need to sit close to get the benefit of HDR. And UHD 4k sets convert HD to 4k'.

A plague of standards

Although Goldman declined to recommend a specific HDR system for use with HDR+, he drew a firm distinction between those that use metadata with the SMPTE 2084 perceptual quantization transfer function (proprietary Technicolor/Philips, proprietary Dolby Vision and the Open HDR10 system used in UHD Blu-ray players and HDR TV sets) and HLG (hybrid log gamma) the system developed by the BBC and NHK, which needs no metadata because it combines 1930s CRT gamma curves with modern logarithmic transfer functions, and relies on a look-up table in the TV to convert the logarithmic camera signal into extremes of light and shade.

Metadata or not?

Says Goldman: 'HDR systems that need metadata are good for pre-produced material but are not good for live broadcasting because you have no way of knowing ahead of time how a scene will change; for instance, you can't say what its maximum brightness will be. HLG does not need metadata; it can be backwards compatible with SDR sets'.

SES is currently using HLG for all its demo channels, confirms Thomas Wrede, VP Reception Systems, SES.

'We believe in metadata' countered Teddy Florent of Technicolor, robustly defending its use as the best way to get the best HDR pictures.

'It doesn't matter what lab tests show' responded Goldman. 'In the real world you don't know what the final stage of the broadcast compression chain is and what it is doing to the signal.'

The good news, Matthew Goldman summed up, is that there should be a standards lock down that makes HDR+ implantation possible by 2016 or 2017 at the latest. The bad news, he added, is that the standards will not select one HDR solution.

But receiver chip sets are due soon from a wide variety of vendors, assured Teddy Florent, and they will support at least the main four HDR solutions, HDR10, HLG, Dolby and Technicolor.

What's in a name?

Paradoxically, the biggest obstacle to HDR+ may be semantic rather than technical.

Although an HDR+ option is already buried in the Picture menu of recent Samsung UHD TVs, its function does not tally with what Goldman means by HDR+.

'I coined the term 'HDR+' around 2+ years ago', says Goldman. 'You can find lots of published articles/presentations on the web by searching for my name and HDR. It seems that Samsung either independently coined the same term or decided my name was cool and adopted it. From what I understand, the function it invokes in a Samsung TV is unrelated to what I mean by HDR+. Samsung appears to use that term for their proprietary method of "stretching" the SDR colour volume to simulate an "HDR-like" experience'.

Subsequent round-robin questioning shows that most of the major TV manufacturers are in similar lack of agreement over what 'HDR+' means to them.

The BBC failed to comment on progress with HLG testing.

But Neema Shah Khan, Senior Brand and Partnerships Manager, Freeview, assures: 'Any industry feature that can enhance the consumer viewing experience is welcomed by Freeview. This technology is still in its early stages. Further testing, collaboration and agreement from broadcasters and manufactures are still needed.'

Solar system GPS

An accurate method for enabling autonomous spacecraft location and navigation has taken a leap forward thanks to work at the National Physical Laboratory (NPL) and the University of Leicester. Researchers have published a paper in *Experimental Astronomy* that reveals a spacecraft's position in space in the direction of a particular pulsar can be calculated autonomously, using a small X-ray telescope on board the craft.

The method uses X-rays emitted from a pulsar, which can be used to work out the position of a craft in space in 3D to an accuracy of 30km at the distance of Neptune. Pulsars are dead stars that emit radiation in the form of X-rays and other electromagnetic waves. For a certain type of pulsar, called 'millisecond pulsars', the pulses of radiation occur with the regularity and precision of an atomic clock and could be used much like GPS in space.

The paper details simulations undertaken using data, such as the pulsar positions and a craft's distance from the Sun, for a European Space Agency feasibility study of the concept. The simulations took these data and tested the concept of triangulation by pulsars with current technology (an X-ray telescope designed and developed by the University of Leicester) and position, velocity and timing analysis undertaken by NPL. This generated a list of usable pulsars and measurements of how accurately a small telescope can lock onto these pulsars and calculate a location. Although most X-ray telescopes are large and would allow higher accuracies, the team focused on technology that could be small and light enough to be developed in the future as part of a practical spacecraft subsystem.

IBM lab-on-a-chip to detect cancer

IBM scientists have developed a new lab-on-a-chip technology that can separate biological particles at the nanoscale and could help enable physicians to detect diseases such as cancer before symptoms appear.

Lab-on-a-chip technologies have become an incredibly helpful tool as they can be significantly faster, portable, easy to use and require less sample volume to help detect diseases. The goal is to shrink down to a single silicon chip all of the processes necessary to analyse a disease that would normally be carried out in a full-scale biochemistry lab.

Using a technology called nanoscale deterministic lateral displacement, or nano-DLD, IBM researchers have developed technology that allows a liquid sample to be passed through a silicon chip containing an asymmetric pillar array. This array allows the system to sort a microscopic waterfall of nanoparticles, separating particles by size down to tens of nanometers resolution. IBM has already scaled down the chip size to 2cm by 2cm.

For diagnosis applications, the IBM team targeted biological particles called 'exosomes'. These range in size from 20-140nm and contain information about the health of the originating cell that they are shed from. A determination of the size, surface proteins and nucleic acid cargo carried by exosomes can give essential information about the presence and state of developing cancer and other diseases. Exosomes are released in easily accessible bodily fluids such as blood, saliva or urine. They represent a precious biomedical tool as they can be used in the context of less invasive liquid biopsies to reveal the origin and nature of a cancer.

Smart Board – a new development PCB

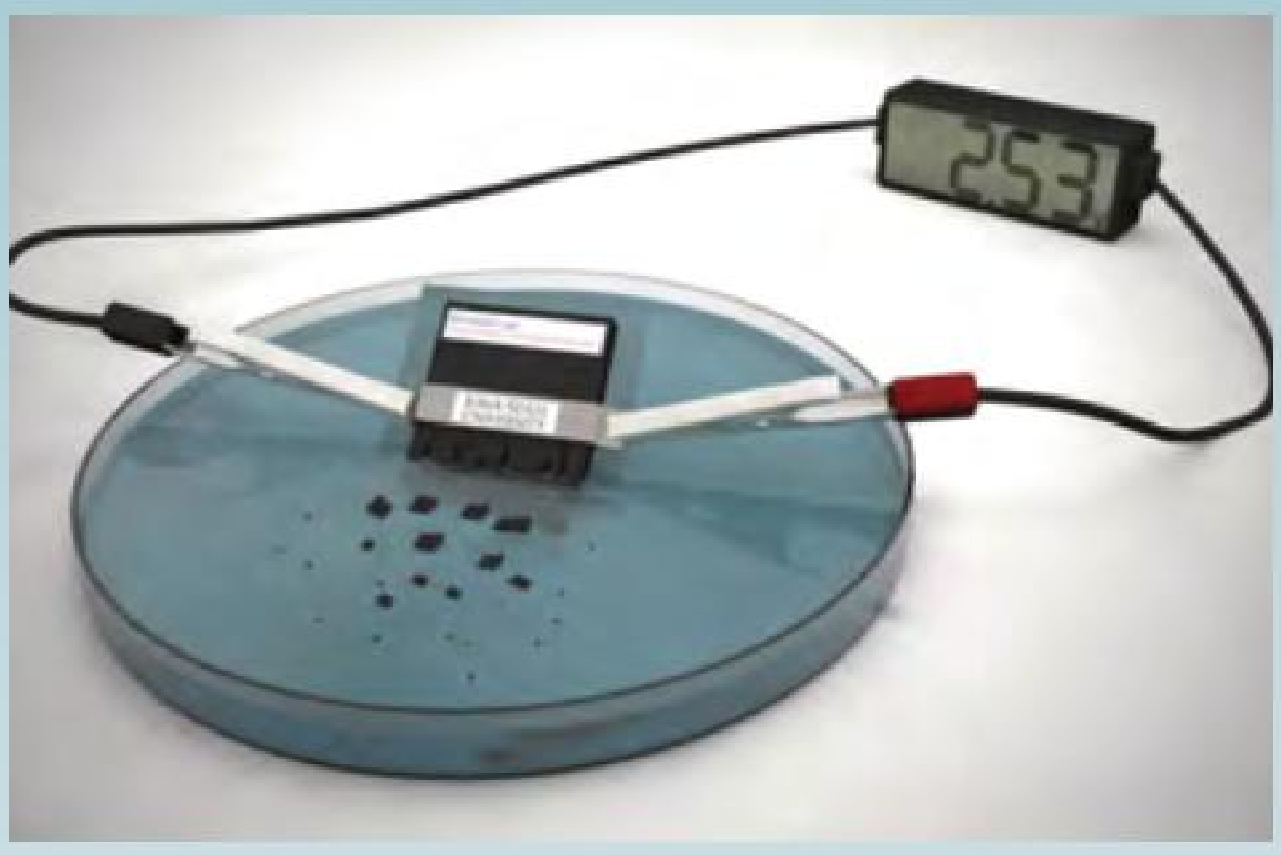
Engineers at Myelectronicstec.com have invented a prototype board that is easy to work with and ideal for hobbyists and professionals. It bridges the gap between Veroboard and tag strips, and is designed to take larger components.

'Smart Board' is made to the same standards as a commercial PCB. It has pads for popular voltage regulators like the 7805 series and is ideal for power supplies and amplifiers. The PCB has multiple voltage rails and tracks running horizontally and vertically. There are just over 400 0.8mm holes, so it is ideal for larger components like diodes and large resistors. Standard mounting blocks for power supplies mount straight onto the matrix of holes which have 5mm spacing. It also features 3mm mounting holes for nylon pillars.

Measuring 97mm × 214 mm and weighing 170 grams, it can be posted to your door by first class mail for just £5. To order, visit **www.myelectronicstec.com** and click on the Smart Board menu, or call 0114 360 5355. Alternatively, enter 'Smart Board' in eBay's search option.

See p.58 in this issue of EPE *for Jake Rothman's Smart Board review.*

Self-destructing battery



Self-destructing electronic devices could keep military secrets out of enemy hands. Or they could save patients the pain of removing a medical device. Or, they could allow environmental sensors to wash away in the rain.

Making such devices possible is the goal of a relatively new field of study called 'transient electronics'. These transient devices could perform a variety of functions – until exposure to light, heat or liquid triggers their destruction.

Reza Montazami, at the Iowa State University has been working on transient technology for several years, and the latest development from his lab is a self-destructing, lithium-ion battery capable of delivering 2.5V and dissolving or dissipating in 30 minutes when dropped in water. The battery can power a desktop calculator for about 15 minutes.

The battery is constructed from electronics printed on a single layer of a degradable polymer composite. It is made up of eight layers, including an anode, cathode and the electrolyte separator, all wrapped up in two layers of a polyvinyl alcohol-based polymer. When dropped in water, the polymer casing swells, breaks apart the electrodes and dissolves away.

Bye bye VCR

Most people probably think VCR – video cassette recorders – died years or even decades ago, but in fact the last known manufacturer, Funai Corporation in Japan, has just announced that they are ceasing production. Perhaps, just as surprising, is that this was not due to lack of demand – they managed to shift 750,000 units in 2015 – but because they could no longer source parts.

EPE EVERYDAY PRACTICAL ELECTRONICS

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All change for wireless

TechnoTalk

Mark Nelson

No, not the brown wooden wireless set in the corner of your parents' or grandparents' living room, but the function and purpose of wireless devices. If the Internet of Things is to be a game-changer for the mobile radio industry, as discussed last month, then there's an equal transformation in store for indoor connectivity. Also, has a cyber poacher turned gamekeeper?

BEING A TRADITIONALIST, I DON'T always enjoy change. Why must KISS ('keep it short and simple') now be redefined as the less informative 'keep it simple, stupid'? Or why should we adopt the foreign dialect term of 'train station' when we have the expression 'railway station', which has served us well since the dawn of passenger railways (a British invention!) nearly 200 years ago?

Wirefree world

For this reason, I prefer to use the broader concept of 'wirefree' for systems that may involve optical as well as radio-frequency transmission, leaving 'wireless' for traditional radio broadcasting. After that small – but vital – detour, I can now come to the main point of this month's commentary, namely another radical change in the nature of domestic, office and industrial networking.

As a clued-up, tech-savvy reader of *EPE* magazine, it's a fair guess that you employ Wi-Fi, Bluetooth or Zigbee at home and/or at work. And if you do, the chances are that you'll be using it for streaming audio or video to a smartphone or fixed media centre set-up, and computing on a tablet or laptop or some other fairly prosaic function of this kind. Well, it's time to wise up. According to research and analysis firm ABI Research, sensors and connected peripherals already outnumber the smartphones and PCs that use our existing wirefree connectivity.

In fact ABI Research forecasts that the global installed base of active wirefree connected devices will top 47 billion by 2021, more than double the current level. Smartphones, PCs, and other 'hub' devices may have accounted for the lion's share of total active connections, with accessories (including peripherals, residential smart lighting and wearable devices) plus sensor nodes (like Bluetooth beacons, proximity sensors, and other 'edge' devices) rounding out the remainder. But from now on it's the accessories and sensor nodes that will benefit most from continued improvements to underlying Internet of Things (IoT) infrastructure.

Says ABI's senior analyst Ryan Martin, 'A compound annual growth rate of 4.1% through to 2021 positions 2016 to be the first year that accessories and sensor nodes are in the majority, rising to more than 65% of total active connections by the end of the forecast period. Growth will be driven by a massive uptick in contextually-aware IoT endpoints across retail, advertising and supply chain, smart home, and industrial IoT markets.' In other words, you won't be able to walk through a shopping mall or past a restaurant without your smartphone being assailed by special offers to tempt you to spend your money.

Breathless

Ryan says that, 'the recent convergence of low-power wide area, short-range wireless and cellular networks represents a fertile battleground for the future of IoT enablement. Whereas today just 55% of IoT connections can be attributed to the digital-first domain (the Internet of Digital), the emergence of low-power wide-area and short-range wireless network technologies that have been purpose-built for the IoT puts the physical-first domain (IoT) on track to account for 65% of active wireless connections in the next five years.' He concludes breathlessly: 'Advances in mesh networking, location-aware ICs, and better utilisation of unlicensed spectrum are among the key ingredients driving wireless sensor network deployments, and, in turn, the next generation of connected devices.'

Does this sound a bit rich to you?

When I read the headline 'The global cyber security challenge' in the same sentence as the name Huawei, I had to smile. No need to ask 'Who are we?' (the anglicised pronunciation of this Chinese electronics giant's name), as my mind flashed back to a previous controversy surrounding this very successful manufacturer's products. At the end of 2013 Jacob Appelbaum of the German news magazine *Der Spiegel* asserted that he had found proof that networking products made by Huawei included illicit 'backdoor' functionality that made them vulnerable to spying exploits. In turn, this was the central reason why US Senators banned Huawei from taking US government projects, claiming that the company was a tool of the Chinese military.

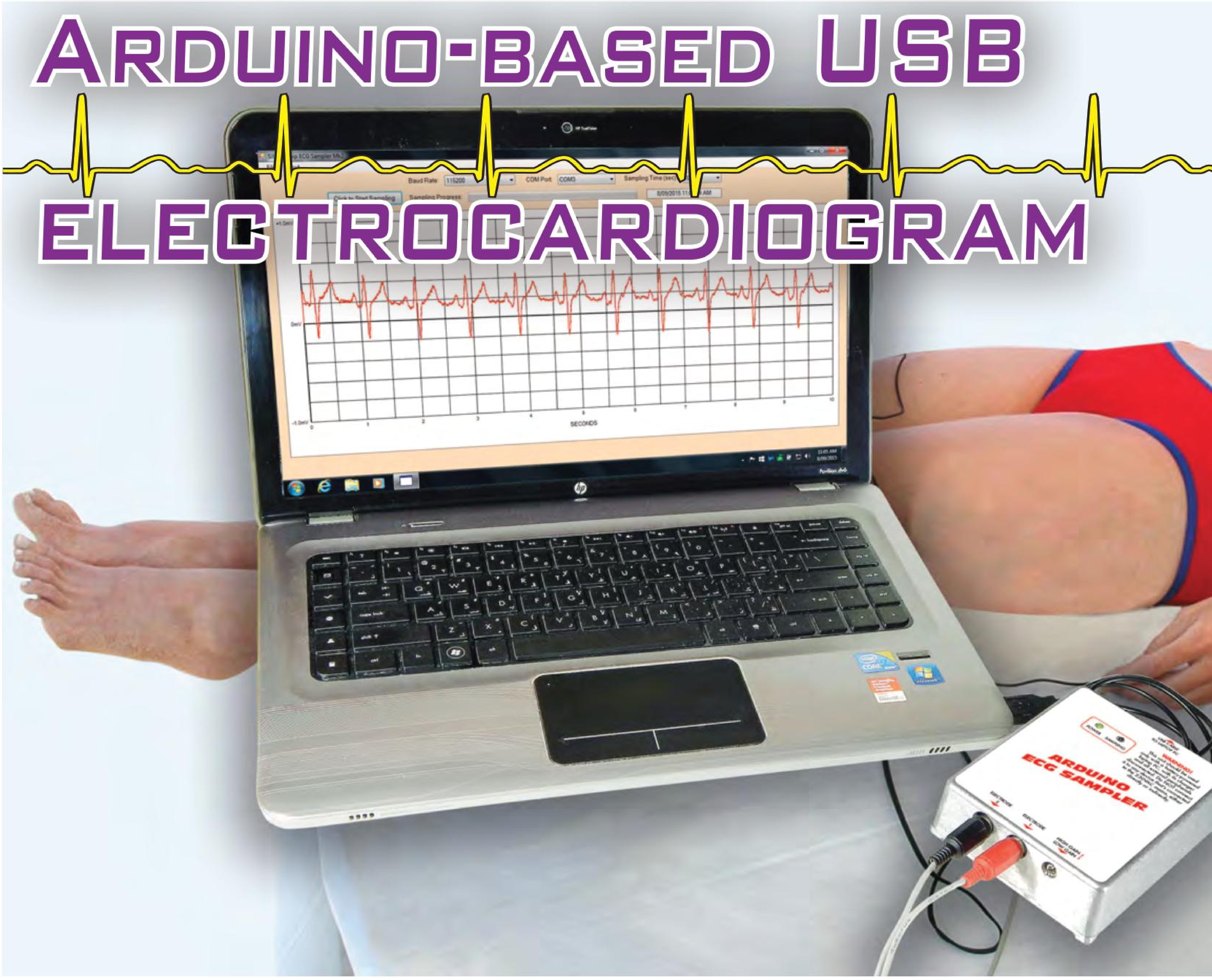
But as Appelbaum explained, the problem was that these backdoors in the Huawei gear were put there because 'US spooks wanted to spy on everyone and the Chinese outfit was just doing what it was told'. Three months later the *New York Times* revealed the full extent of this clandestine activity, backed up by material provided by former National Security Agency contractor Edward Snowden (**www.nytimes.com/2014/03/23/world/asia/nsa-breached-chinese-servers-seen-as-spy-peril.html?_r=1**). One of the consequences of this affair is that many governments now preclude the use of Huawei networking equipment in any part of their sensitive national communications infrastructure.

Reformed character

Perhaps hurt by past negative publicity, the Huawei company has released a series of four technical white papers on the subject of cyber security. The latest, released in July, carries the title of *The Global Cyber Security Challenge* and discusses how to ensure cyber security, sharing best practice techniques and calling for accelerated efforts to collaborate to address the common challenge. The content is decidedly technical but you can download it at: **www.huawei.com/en/news/2016/6/2016-Cyber-Security-White-Paper**

It's no secret of course that Google's well-regarded flagship Nexus 6P smartphone is built by Huawei and there has been no suggestion that Huawei is bugging what you get up to. As other commentators have pointed out, the Chinese government isn't interested in the data or online activity of individual users. If it is spying on anybody or anything, it's state secrets that it would be targeting. Huawei founder Ren Zhengfei has denied any involvement in state-sponsored cyber espionage and it is stated that the malware that can listen to calls, track users and make online purchases found pre-installed on smartphones made by Huawei and 24 other models of Chinese smartphones was installed by middlemen, not the manufacturers.

ARDUINO-BASED USB ELECTROCARDIOGRAM



Here's an easy-to-build Arduino project which will let you take your own electrocardiogram (ECG) and display it on a laptop PC. The software lets you read, display, save and print the electrical waveform generated by your heart – or anyone else's. It connects to your laptop via a USB cable, which also provides the low power it needs to operate.

AN ELECTROCARDIOGRAM or 'ECG' is a piece of medical equipment used to measure and record the voltages produced as a result of heart muscle activity. By attaching a pair of electrodes (or 'leads' as they are known in the trade) to the skin of your wrists, ankle or chest, this PC-Driven ECG project can display, record or print out the same kind of ECG waveform via your personal computer.

Why build an ECG? Just looking at the waveforms generated by your heart can be both fun and educational. You can monitor changes to your heart under various conditions, as your heart is affected by many things including emotions and mental and physical activity – even breathing.

All of these factors have a demonstrable effect on the heart's ECG waveform. Being able to show this easily, safely and at low cost is an added bonus.

Professional ECG machines can cost thousands of pounds, and while this project is not intended to be used as a diagnostic device, the displayed, recorded and printed waveforms are of a quality approaching that of professional machines.

This design is based on a low-cost Arduino Uno/Freetronics Eleven microcomputer module, which controls the actual sampling and sends the samples back to the laptop.

Note that to ensure complete safety, the unit should only be used with a laptop PC running on batteries and disconnected from all other external

By JIM ROWE

DISCLAIMER

This project has not been designed for medical diagnosis. Correct interpretation of ECG waveforms and tracings is a complex and skilled procedure and requires proper medical training. The USB/ECG is presented here as an instructive and educational device only. If you are concerned about the health of your heart, consult your GP or a heart specialist.

devices. It should not be used with a PC (desktop or laptop) connected to the 230V mains supply – see warning panel later in this article.

Arduino shield

It does this under the direction of a small firmware program ‘sketch’ stored in the micro’s flash memory. To adapt the Arduino module for sampling the low-level signals picked up by ECG electrodes, we have designed a front-end ‘shield’ module which plugs into the top of the Arduino module in the usual way.

The shield provides a high-gain (1000×/2000×) differential amplifier input stage, plus a three-pole low-pass filter to reduce the sampler’s susceptibility to 50Hz hum.

The Arduino and *ECG Sampler* Shield are powered from the laptop PC via the USB cable, so there’s no need for a separate power supply. The total current drawn by the sampler is less than 65mA.

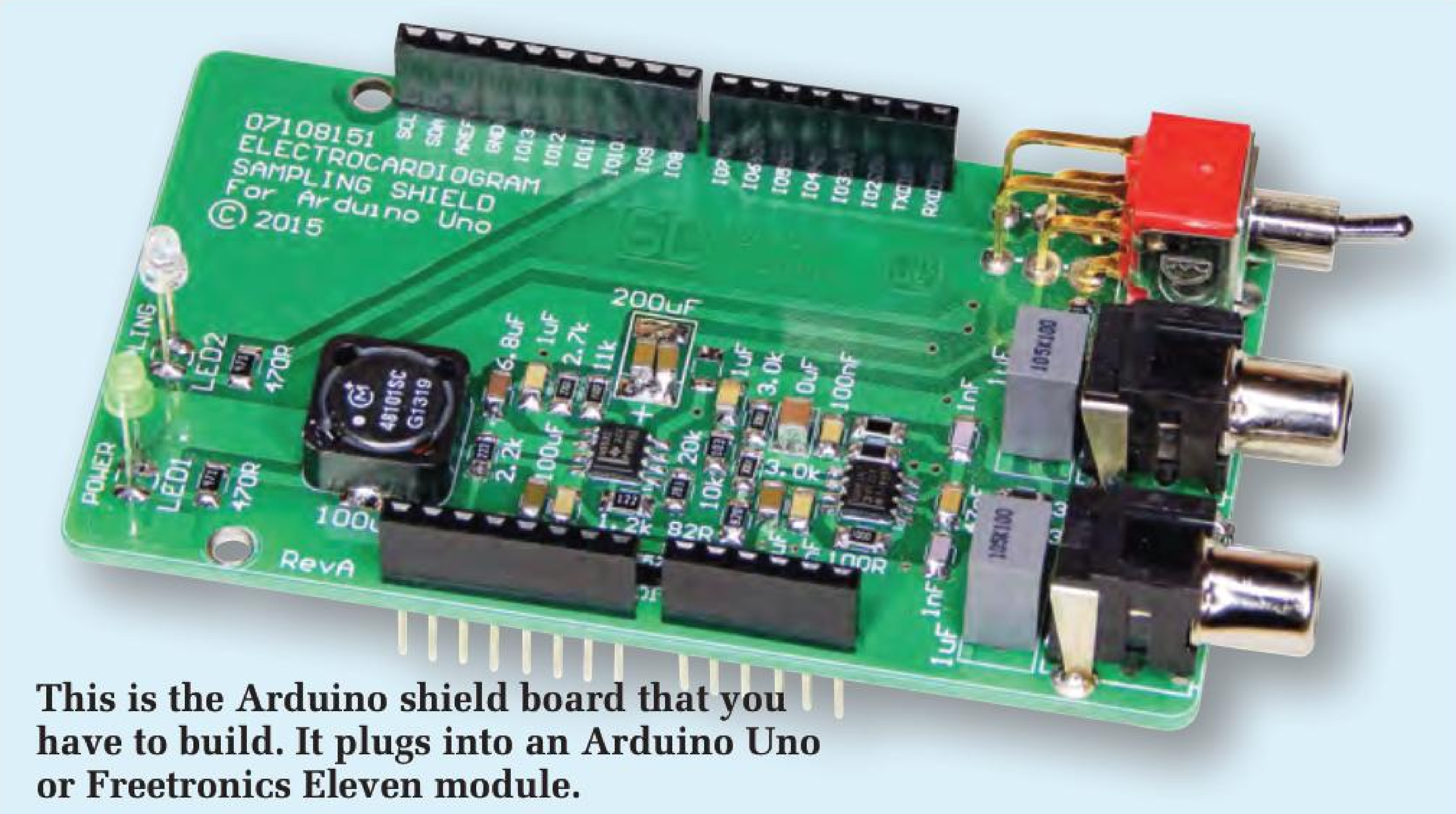
It’s easy to use, with all the Sampler’s functions controlled by a Windows-based GUI program running on the laptop PC and written in Visual C++. Both the Arduino micro’s firmware program sketch and the Visual C++ PC program executable can be downloaded from the *EPE* website.

To allow the laptop to communicate with the Arduino via a USB cable, you’ll also have to download and install a special USB virtual COM port driver. This can be downloaded from either the main Arduino website or the Freetronics website.

While you’re hooked up to the Arduino website, you’ll also need to download and install the latest version of the Arduino IDE (integrated development environment) package. That’s because you’ll need this to upload our sampling firmware sketch to your Arduino micro (more about all this later).

How it works

The project is essentially in two parts: 1) a standard Arduino microcomputer



This is the Arduino shield board that you have to build. It plugs into an Arduino Uno or Freetronics Eleven module.

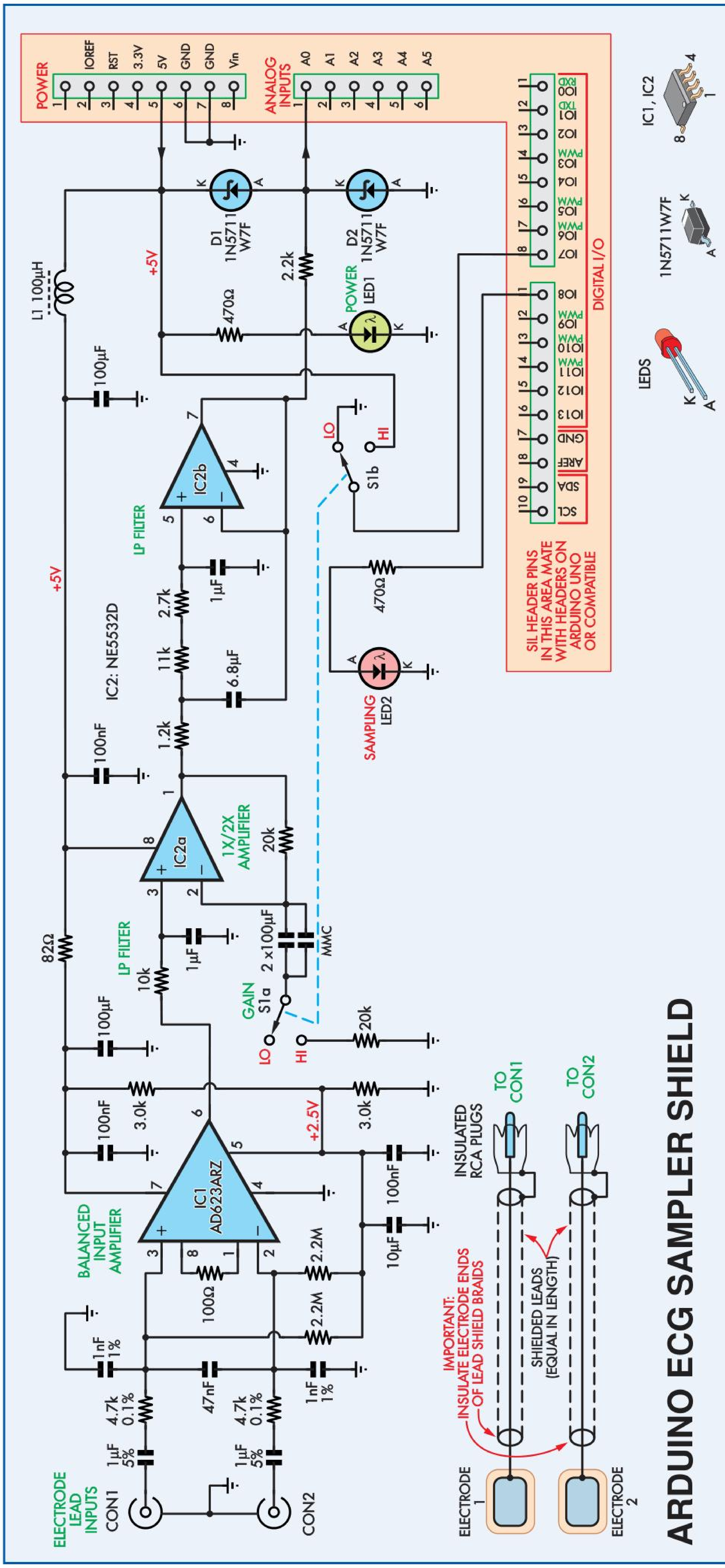

ARDUINO ECG SAMPLER SHIELD
POWER
IOREF
RST
3.3V
5V
GND
GND
Vin
ANALOG INPUTS
A0
A1
A2
A3
A4
A5
DIGITAL I/O
SIL HEADER PINS IN THIS AREA MATE WITH HEADERS ON ARDUINO UNO OR COMPATIBLE
L1 100µH
100µF
+5V
D1 1N5711 W7F
D2 1N5711 W7F
470Ω
2.2k
POWER LED1
SAMPLING LED2
IC2b
LP FILTER
IC2: NE5532D
2.7k
11k
1.2k
1µF
6.8µF
S1b
LO
HI
IC2a
1X/2X AMPLIFIER
20k
2 x100µF
MMC
GAIN S1a
10k
82Ω
100nF
3.0k
+2.5V
IC1 AD623ARZ
BALANCED INPUT AMPLIFIER
100Ω
2.2M
10µF
1nF 1%
47nF
4.7k 0.1%
1µF 5%
ELECTRODE LEAD INPUTS
CON1
CON2
INSULATED RCA PLUGS
TO CON1
TO CON2
IMPORTANT: INSULATE ELECTRODE ENDS OF LEAD SHIELD BRAIDS
SHIELDED LEADS (EQUAL IN LENGTH)
ELECTRODE 1
ELECTRODE 2
IC1, IC2
1N5711W7F
LEDS
K
A

Fig.1: the *ECG Sampler* Shield circuit uses just two ICs. The low-level ECG signals from the electrodes are first amplified by differential amplifier IC1, a specialised instrumentation amplifier. Its output is then low-pass filtered and amplified by op amp IC2a, while IC2b provides additional low-pass filtering to reduce 50Hz hum.

module which does the ADC (analogue-to-digital conversion) sampling and sends the samples back to the laptop PC; and (2) the high-gain *ECG Sampler* Shield which you need to build. We'll discuss the operation of the shield first.

The muscles of the human body are controlled by electrochemical impulses which are distributed by the nervous system. On reaching their destination, the nerve impulses cause the muscles to contract and produce much larger electrical voltages. A small proportion of these voltages is conducted out to the surface of the skin, where they can be detected using sensitive equipment like an ECG.

Because the heart is a large, complex group of muscles which contract cyclically in a preset sequence (see panel), it's possible to study its overall condition by measuring the amplitude, timing and waveform of the heart muscle voltage components found on the skin.

This is the reason for capturing ECG waveforms, which are obtained using two or more electrodes attached to the skin via a conductive saline solution or paste.

Capturing ECG waveforms is quite a challenge, because the voltage components found on the surface of the skin are quite low in amplitude – around 1mV peak-to-peak, depending on the positions of the electrodes and the resistance between them and the skin. That's about 1/10,000th of the voltage of a standard 9V battery!

So we need to feed these tiny voltages through a high-gain amplifier, to display or record them. To make the job that much harder, the tiny voltages we want to measure are usually completely swamped by 50Hz hum, picked up by our bodies from the fields surrounding the AC wiring in our homes and offices.

Fortunately, we are only interested in the voltage differences between the two electrodes that are being used, whereas the 50Hz hum picked up by the electrodes is virtually the same regardless of their position on the body. In other words, the 50Hz hum is a 'common-mode' signal, while the tiny ECG voltages are 'differential-mode' signals.

By using a highly-balanced differential amplifier as the input stage of the ECG amplifier, we can cancel out most of the common-mode 50Hz hum before the differential ECG voltages are amplified. By the way, the connections between the electrodes and your skin play an extremely important role in this hum cancellation, because if one connection is poor, this can upset the balance of the input amplifier.

Most of the remaining 50Hz signals are removed by low-pass filtering in the later stages of the amplifier. So the output of the amplifier provides relatively clean amplified ECG signals, with little residual 50Hz hum.

Circuit details

You can see how this is all done by referring to the circuit of Fig.1. The shielded electrode leads are brought into the *ECG Sampler* Shield via connectors CON1 and CON2 and then fed through 1µF capacitors and series 4.7kΩ resistors to the inputs of IC1.

IC1 is an Analog Devices AD623-ARZ, a specialised instrumentation amplifier offering very highly balanced differential inputs and hence very high common-mode signal rejection, combined with high gain.

A simplified version of the circuitry inside the AD623 is shown in Fig.2 and it is essentially three op amps in one: two matched-gain input stages feeding a balanced 'subtractor' output stage. The overall AD623 gain for differential-mode signals is set by external resistor Rg, which gives a gain of 1000 times (60dB) when using a value of 100Ω.

To ensure that IC1 can deliver the maximum undistorted output level (and to ensure that the Arduino ADC used for sampling the amplified signals can handle the largest signal swing), we connect IC1's reference signal input (pin 5) to a low-impedance source of +2.5V DC (ie, half the 5V supply). This is provided by a voltage divider comprising two 3.0kΩ resistors, thereby setting the zero-signal output level of IC1 to the same level. The two 2.2MΩ input bias resistors for IC1 are also returned to the same +2.5V point.

Since IC1 operates with such a high gain, we also need to prevent it from amplifying any stray RF signals that may be picked up by the electrode leads (or the subject's body). This is the purpose of the 1nF bypass capacitors on each input of IC1 and also the 47nF capacitor between the two inputs. All three capacitors form a balanced low-pass filter, in conjunction with the two 4.7kΩ input series resistors.

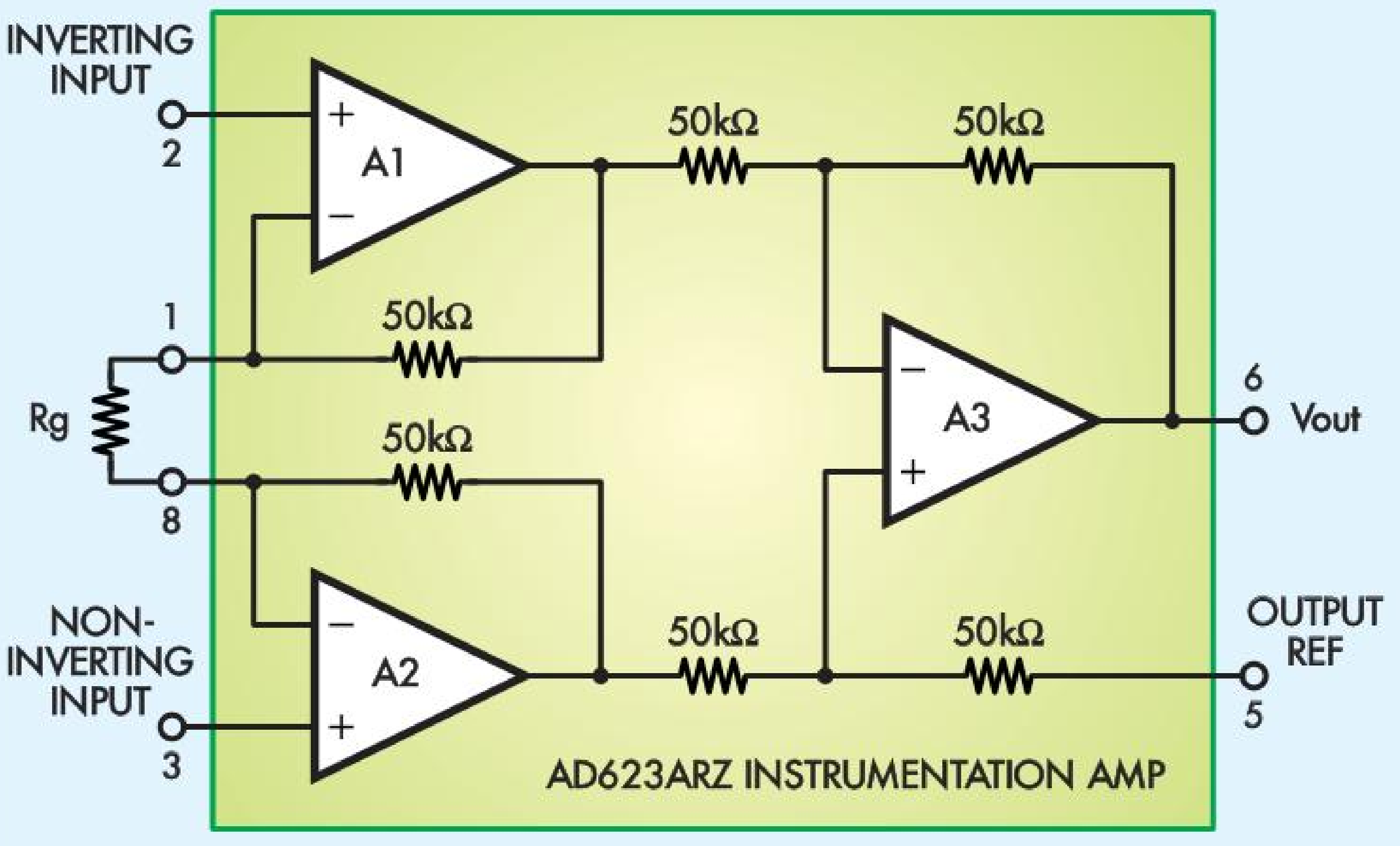

INVERTING INPUT
2
+
–
A1
50kΩ
50kΩ
1
50kΩ
Rg
50kΩ
8
–
A3
+
6
Vout
NON-INVERTING INPUT
3
–
A2
+
50kΩ
50kΩ
OUTPUT REF
5
AD623ARZ INSTRUMENTATION AMP

Fig.2: inside the AD623ARZ instrumentation amplifier. Op amps A1 and A2 are matched gain input stages and these feed a balanced subtractor output stage based on op amp A3. The resistors are laser-trimmed to achieve the required precision.

The rest of the *ECG Sampler* Shield's amplifier and filter circuitry is based around IC2, an NE5532D dual low-noise op amp. The output from IC1 is fed to the input of IC2a via a low-pass filter formed by a series 10kΩ resistor and a 1µF capacitor, to give a corner frequency of about 17Hz and an attenuation of about 9dB at 50Hz.

IC2a provides a small amount of fixed amplification for the ECG signals. The gain here is 1× or 2×, as set by switch S1. The LO position of the switch gives unity gain (1×), while the HI position provides a gain of 2×. The overall ECG signal gain for the two switch positions is thus 1000 and 2000 times, respectively.

IC2b provides additional low-pass filtering, to further reduce 50Hz hum. With the R and C values shown, this filter stage has a corner frequency of about 15Hz and provides a further attenuation of about 21dB at 50Hz. At the same time, it has unity gain for the low-frequency ECG signals.

So, at the output of IC2b (pin 7) we end up with reasonably clean ECG signals (although still with some residual 50Hz hum), amplified either 1000 or 2000 times, depending on the setting of S1.

Diodes D1 and D2, together with the series 2.2kΩ resistor, ensure that the amplified ECG output signals fed out to the Arduino ADC via the A0 pin are prevented from swinging below –0.3V

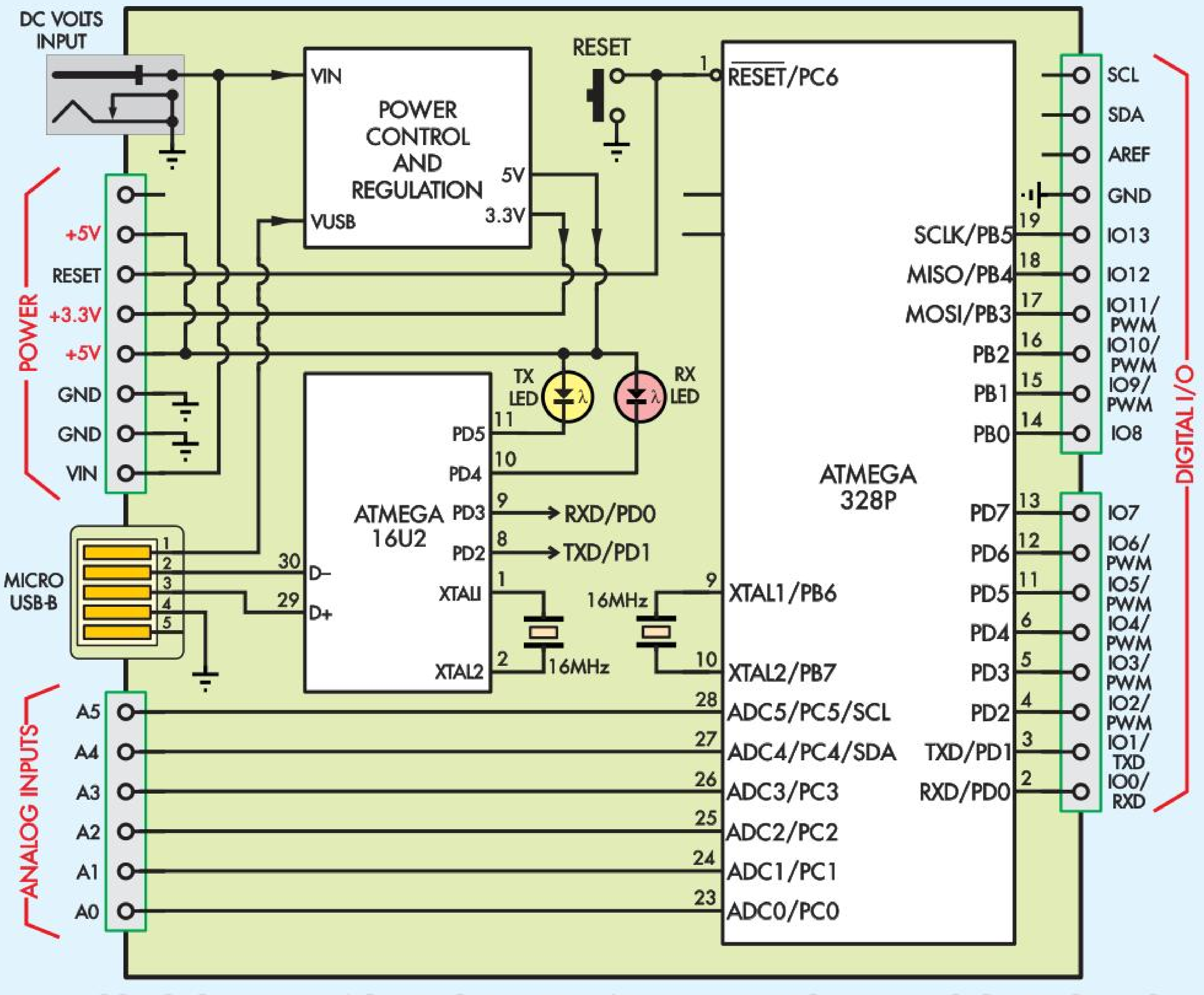

DC VOLTS INPUT
VIN
POWER CONTROL AND REGULATION
5V
3.3V
VUSB
RESET
1
RESET/PC6
SCL
SDA
AREF
GND
POWER
+5V
RESET
+3.3V
+5V
GND
GND
VIN
TX LED
RX LED
PD5
PD4
11
10
ATMEGA 16U2
PD3
PD2
9
8
RXD/PD0
TXD/PD1
XTALI
XTAL2
16MHz
16MHz
MICRO USB-B
1
2
3
4
5
30
D–
29
D+
9
XTAL1/PB6
10
XTAL2/PB7
ATMEGA 328P
SCLK/PB5
MISO/PB4
MOSI/PB3
PB2
PB1
PB0
19
18
17
16
15
14
IO13
IO12
IO11/PWM
IO10/PWM
IO9/PWM
IO8
PD7
PD6
PD5
PD4
PD3
PD2
TXD/PD1
RXD/PD0
13
12
11
6
5
4
3
2
IO7
IO6/PWM
IO5/PWM
IO4/PWM
IO3/PWM
IO2/PWM
IO1/TXD
IO0/RXD
DIGITAL I/O
ANALOG INPUTS
A5
A4
A3
A2
A1
A0
28
ADC5/PC5/SCL
27
ADC4/PC4/SDA
26
ADC3/PC3
25
ADC2/PC2
24
ADC1/PC1
23
ADC0/PC0

Fig.3: block diagram of the Arduino Uno/Freetronics Eleven module. It's based on two Atmel microcontroller chips: an ATmega328P and an ATmega16U2. The 328P micro is used as the module's main CPU, while the 16U2 handles communication with the PC via the module's USB port.

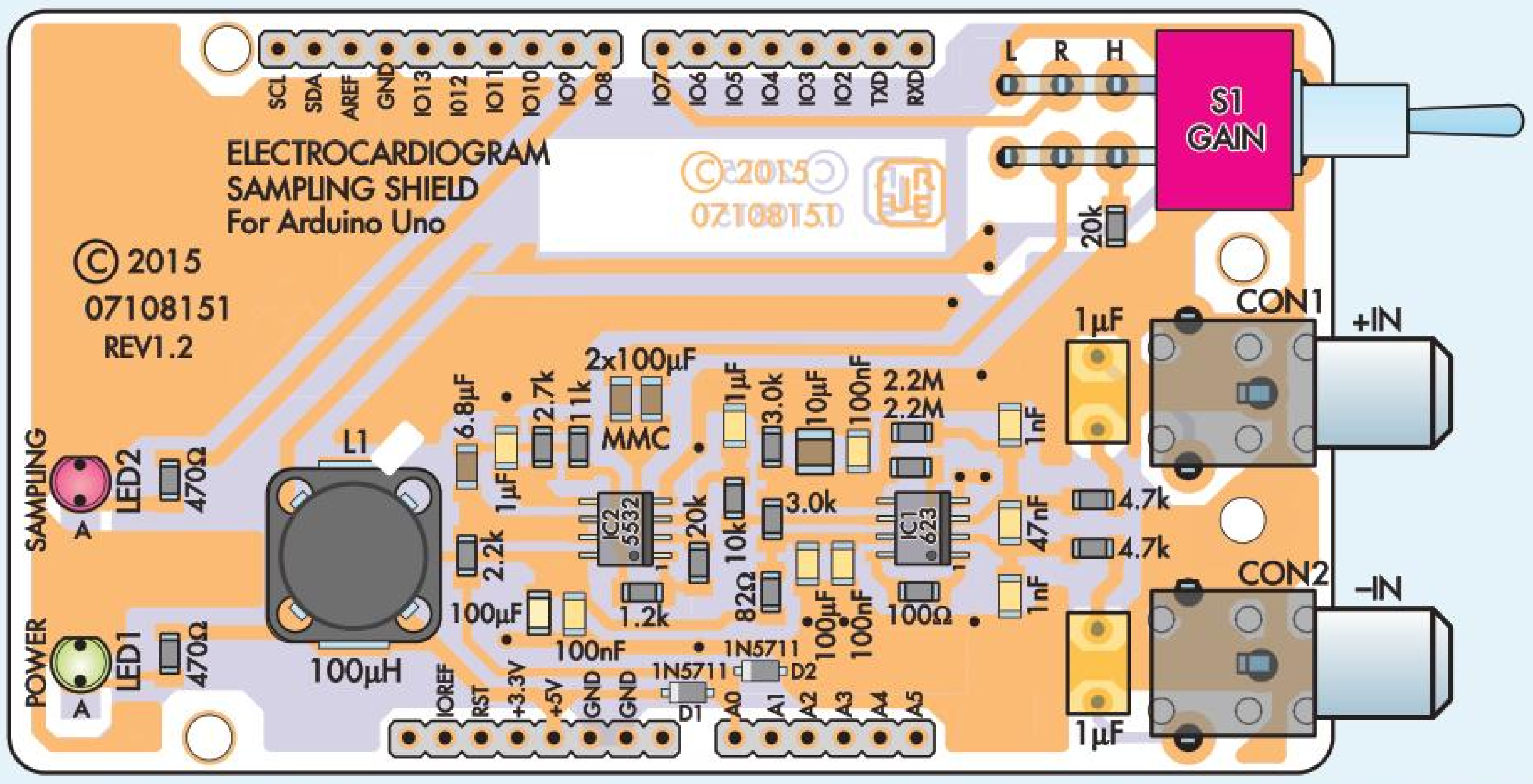
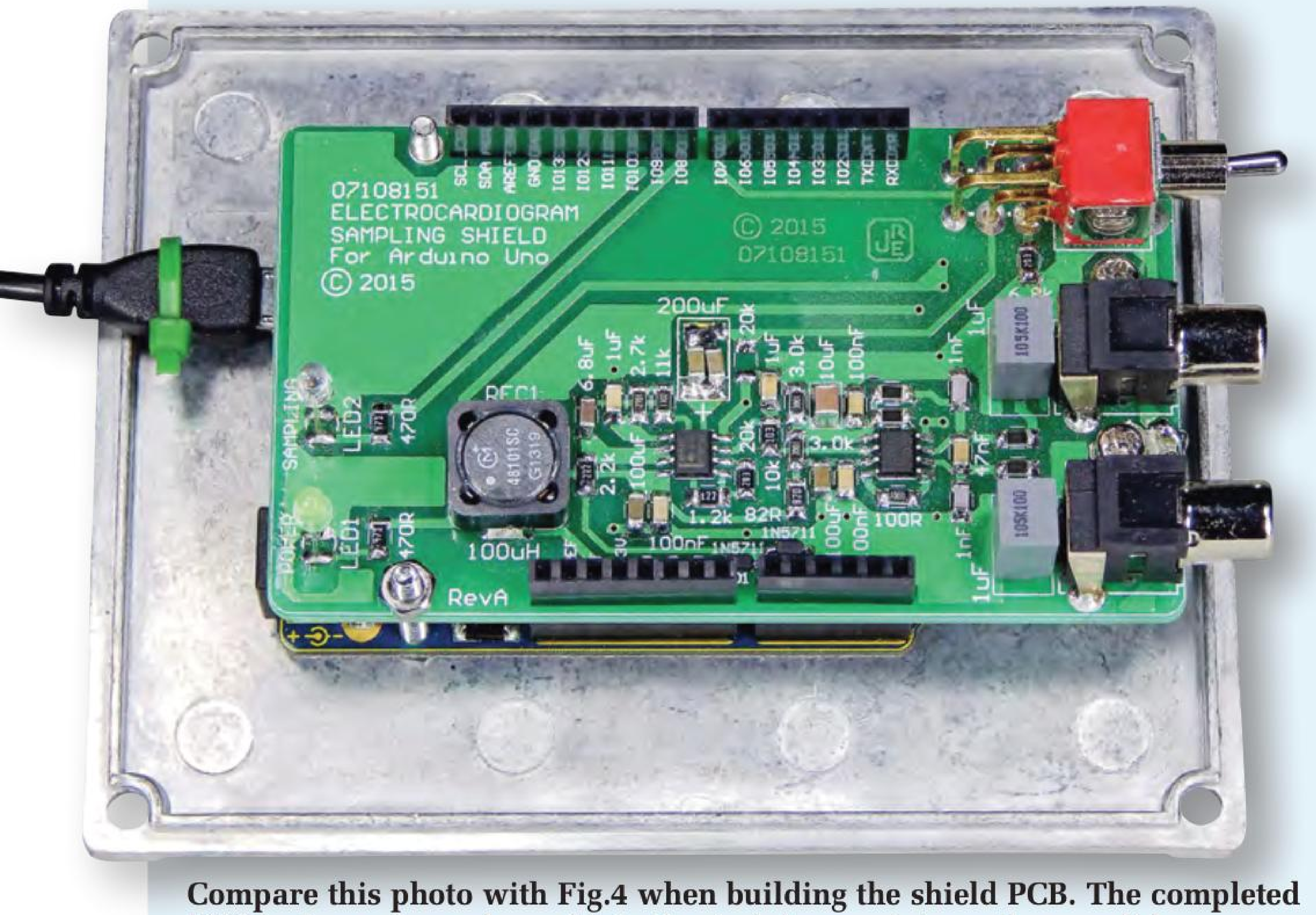

SCL
SDA
AREF
GND
IO13
IO12
IO11
IO10
IO9
IO8
IO7
IO6
IO5
IO4
IO3
IO2
TXD
RXD
L
R
H
S1
GAIN
ELECTROCARDIOGRAM
SAMPLING SHIELD
For Arduino Uno
© 2015
07108151
REV1.2
20k
1µF
CON1
+IN
2x100µF
6.8µF
2.7k
11k
MMC
1µF
3.0k
10µF
100nF
2.2M
2.2M
1nF
L1
IC2
5532
20k
10k
3.0k
IC1
623
4.7k
4.7k
47nF
SAMPLING
LED2
470Ω
A
1µF
2.2k
1.2k
82Ω
100µF
100nF
100Ω
1nF
CON2
–IN
100µF
100nF
1N5711
D2
POWER
LED1
470Ω
A
100µH
IOREF
RST
+3.3V
+5V
GND
GND
VIN
D1
A0
A1
A2
A3
A4
A5
1µF

Fig.4: follow this parts layout diagram to build the shield PCB. Fit the SMD devices first before installing the larger through-hole components (see text).



Compare this photo with Fig.4 when building the shield PCB. The completed PCB is shown here plugged into the Arduino module on the case lid.

or above +5.3V. This is to protect the Arduino's ADC input from overload damage.

The purpose of the second pole of gain switch S1b is to allow the Arduino to sense the current switch position, so that it can inform the software running in the laptop. As shown, S1b's rotor is connected to the Arduino's IO7 pin (used as an input), so this pin is pulled low (ie, to 0V) in the LO switch position and high (+5V) in the HI gain position.

The only other main circuit components are indicators LED1 and LED2. LED1 is a power indicator, to show that the *ECG Sampler* is connected to your laptop and 'ready to roll'. LED2 is turned on by the Arduino during sampling via the IO8 pin, to indicate that sampling is taking place.

Arduino in brief

Now let's take a quick look at the other half of the *ECG Sampler*: the Arduino Uno microcomputer module, or its 100% compatible Australian incarnation, the Freetronics Eleven.

Arduino Uno seems to have been the one primarily responsible for Arduinos becoming a worldwide phenomenon so quickly. The Freetronics Eleven is a direct equivalent of the latest version of the Uno, so when we talk about one we're also talking about the other.

Basically, they're a very compact (69 × 54mm) single-PCB microcomputer based on two Atmel microcontroller chips: an ATmega328P and an ATmega16U2. The 328P device is used as the module's main CPU, while the 16U2 is used to handle communication with the laptop via the module's USB port.

There's not much else, apart from a few low-level chips used for power control and regulation.

Inside the 328P there's a reasonably fast 8-bit RISC processor with 32 8-bit working registers, 32Kbytes of Flash memory, 1Kbyte of EEPROM and 2Kbytes of static RAM. There are also two 8-bit timer/counters, one 16-bit timer/counter, a real-time counter with its own oscillator, six PWM channels, six 10-bit ADC input channels, a programmable serial USART, a master/slave SPI serial interface, an I^2C compatible byte-oriented 2-wire serial interface and an on-chip analogue comparator.

The 16U2 device is actually not far behind the 328P in capability, with 16Kbytes of self-programmable Flash memory, 512 bytes of EEPROM and 512 bytes of internal SRAM. It also provides 8-bit and 16-bit timer/counters, three 8-bit PWM channels, an analogue comparator and so on.

More importantly, it provides a full speed USB 2.0 communications module, with a 48MHz PLL (phase-locked loop), 176 bytes of USB DPRAM for endpoint memory allocation, four programmable endpoints and the ability to handle bulk, interrupt and isochronous transfers with a programmable packet size of up to 64 bytes and single or double buffering.

Fig.3 shows the simplified Uno/Eleven configuration. On the right is the 328P CPU, with its 14 digital I/O pins brought out on its right and its six ADC inputs at lower left. It uses a 16MHz crystal for its main clock (on pins 9 and 10), while a tiny reset switch is connected to pin 1 (for emergency use only).

At centre left is the 16U2, with its USB data pins (29 and 30) connected to the corresponding pins on the USB socket. It also uses a 16MHz clock crystal, which forms the reference for the internal PLL (3 × 16MHz = 48MHz) driving the USB module.

The Uno/Eleven provides a choice of either deriving its power from the laptop via the USB cable or from an external 7-12V DC source via a 2.1mm concentric power socket (at upper left in Fig.3). The latter is used mainly when the Arduino is being used in free-standing applications, ie, not connected to a PC.

In the case of the *ECG Sampler* circuit, we derive power from the laptop PC via the USB connector.

If you compare the pin header labels of Fig.3 with those at the right and lower right of the main circuit of Fig.1, you'll see how the two parts of the *ECG Sampler* are interconnected. The shield derives its +5V power via pin 5 of the 8-pin power header and its earth/0V from pins 6 and 7 of the same header (plus pin 7 of the 10-pin digital I/O header).

It provides the amplified ECG signals to pin 1 of the 6-pin Analog Inputs header (A0/ADC0), while S1b's switch rotor connects to pin 8 of the 8-pin digital I/O header (IO7) and LED2 is driven from pin 1 of the digital I/O header (IO8).

When the *ECG Sampler* is working, the sequence of events is quite straightforward. Before the PC software initiates sampling, it sends a request to the Arduino to report the position of gain switch S1. The Arduino sends back a 1-character response, giving that information.

Then, each time the software wants an ECG sample to be taken, it sends a 1-character 'take a sample' command to the Arduino, which gets its ADC to take a 10-bit sample of the amplified ECG signal at its ADC0 input. The sample value is then sent back to the laptop, the overall sampling cycle taking less than 4.13ms.

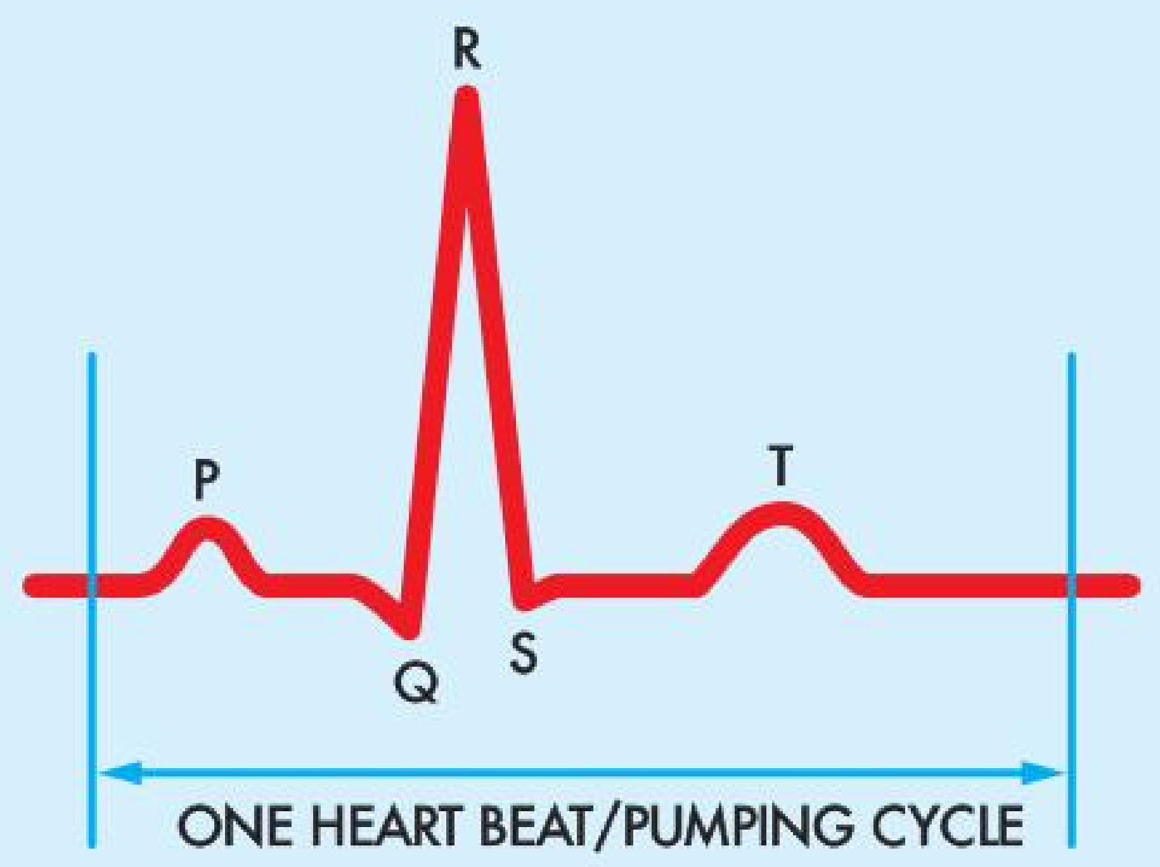
Construction

All the *ECG Sampler* circuitry, except for the Arduino Uno/Eleven microcontroller board, is mounted on the PCB shield. This is designed to plug into the top of the Arduino board in piggyback fashion. The shield PCB which is available from the *EPE PCB Service*, measures 93 × 54mm (only 24mm longer than the Arduino itself, and the same width) and is coded 07108151. The stacked board assembly fits easily inside a standard diecast aluminium box measuring 119 × 93 × 34mm.

The box is used upside down, with the PCB assembly mounted on the inside of the box lid and the box itself lowered down over the assembly to form a shielded enclosure.

The two RCA connectors (CON1 and CON2) used for the ECG electrode leads are accessed through two 12mm-

Your heart and its electrical activity



Most people are aware that the heart is basically a pump that pushes blood around the body via its blood vessel 'plumbing' – the arteries and veins.

A typical human adult heart is about the size of a clenched fist and weighs about 300 grams. It's located near the centre of your chest and pumps about once per second, although this can vary widely due to age, fitness, exertion and health.

The pumping action is triggered mainly by a nerve centre inside the heart, called the sino-atrial (SA) node. Each pumping cycle is initiated by a nerve impulse which starts at the SA node and spreads downwards through the heart via preset pathways.

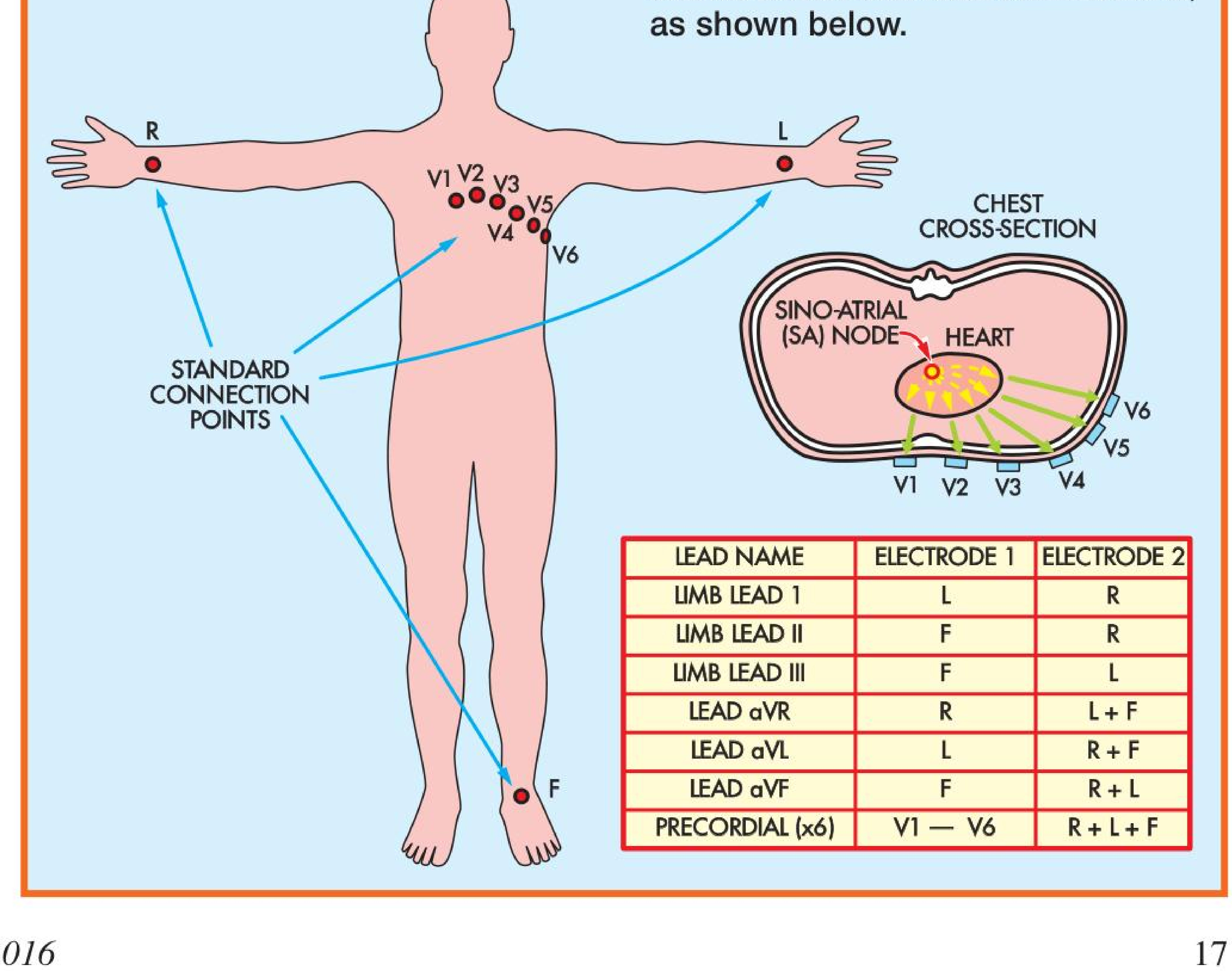
The heart itself is made up of millions of bundles of microscopic muscle cells, which contract when triggered. The muscle cells are electrically polarised, like tiny electrolytic capacitors (positive outside, negative inside), and as the trigger pulse from the SA node passes through them, they depolarise briefly and contract.

With each beat of the heart, a 'wave' of depolarisation sweeps from the top of the heart to the bottom. Weak voltages produced by this wave appear on the outside surface of your skin and can be picked up using electrodes strapped to your wrists, ankle and the front of your chest. It's these voltages (about 1mV peak-to-peak) which are captured and recorded as an electrocardiogram or ECG.

The actual shape and amplitude of the ECG waveform depends on the individual being monitored and the positioning of the electrodes, but the general waveform is as shown above.

The initial 'P' wave is due to the heart's atria (upper input chambers) depolarising, while the relatively larger and narrower 'QRS complex' section is due to the much stronger ventricles (lower output chambers) depolarising. Finally, the 'T' wave is due to repolarisation of the ventricles, ready for another cycle.

Doctors are able to evaluate a number of heart problems by measuring the timing of these wave components and their relative heights. They can also diagnose problems by comparing the way the wave components change with the various standard electrode and lead connections, as shown below.



LEAD NAME	ELECTRODE 1	ELECTRODE 2
LIMB LEAD 1	L	R
LIMB LEAD II	F	R
LIMB LEAD III	F	L
LEAD aVR	R	L + F
LEAD aVL	L	R + F
LEAD aVF	F	R + L
PRECORDIAL (x6)	V1 — V6	R + L + F

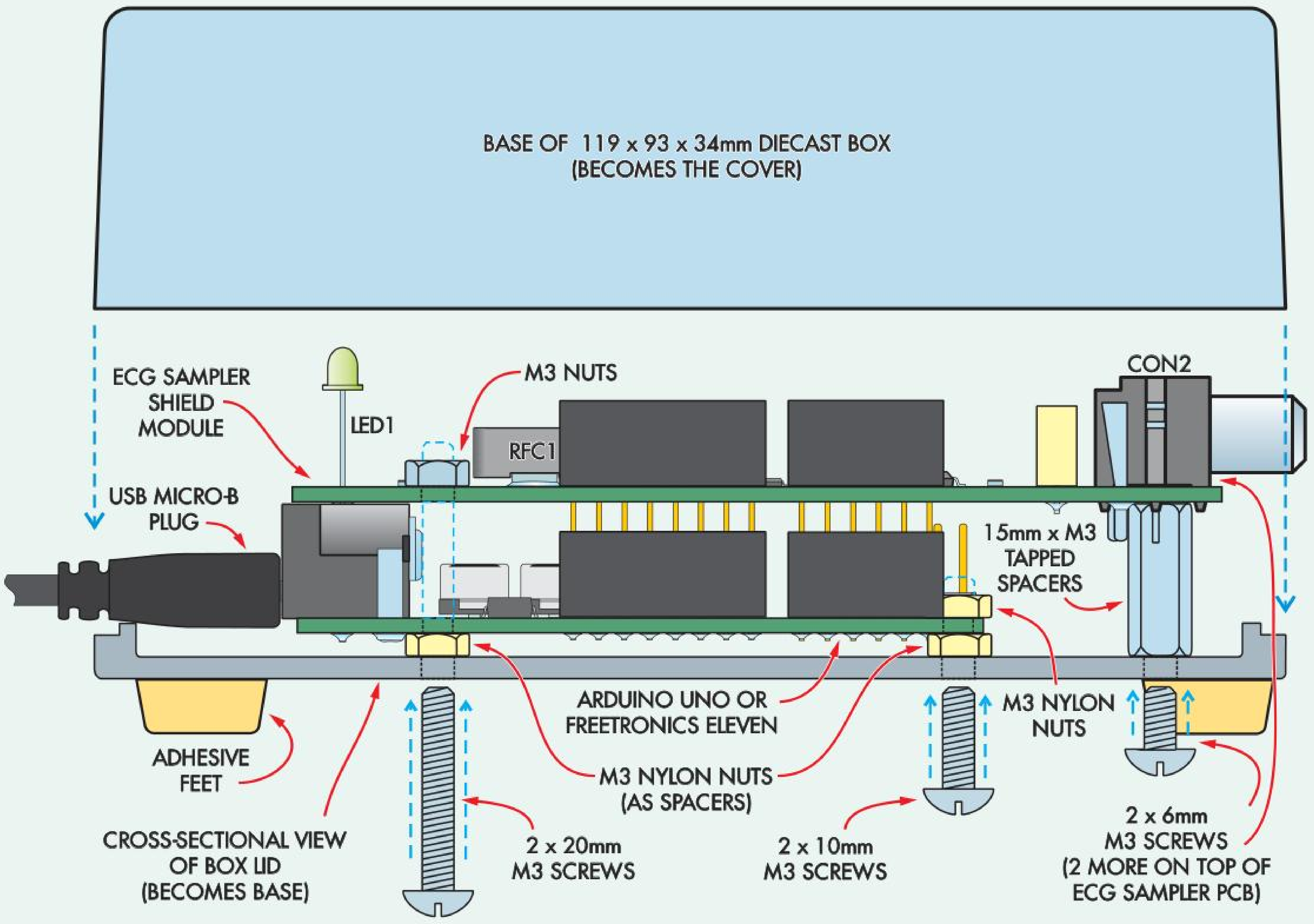

BASE OF 119 x 93 x 34mm DIECAST BOX
(BECOMES THE COVER)
ECG SAMPLER SHIELD MODULE
LED1
M3 NUTS
RFC1
CON2
USB MICRO-B PLUG
15mm x M3 TAPPED SPACERS
ARDUINO UNO OR FREETRONICS ELEVEN
M3 NYLON NUTS
ADHESIVE FEET
M3 NYLON NUTS (AS SPACERS)
CROSS-SECTIONAL VIEW OF BOX LID (BECOMES BASE)
2 x 20mm M3 SCREWS
2 x 10mm M3 SCREWS
2 x 6mm M3 SCREWS (2 MORE ON TOP OF ECG SAMPLER PCB)

Fig.5: this diagram shows how the Arduino module and the *ECG Sampler* Shield board are mounted on the lid of the case. Note that the Arduino module sits on M3 nylon nuts which are used as spacers (do not use metal nuts).

diameter holes in one end of the box, with miniature toggle switch S1 accessible via a 6.5mm-diameter hole in the same end. The two indicator LEDs protrude up through a pair of 3.5mm holes in the 'top' of the box, while a small slot at the far end allows entry of the USB cable.

Most of the components on the *ECG Sampler's* front-end shield PCB are surface-mount devices, the exceptions being input connectors CON1 and CON2, mini toggle switch S1, the two 1µF MKT input capacitors, the two LEDs and the four SIL headers used for the interconnections to the Arduino module.

Fig.4 shows the parts layout on the shield PCB. We suggest that you fit the SMD resistors first, followed by the SMD capacitors and then the diodes (D1 and D2) and ICs (IC1 and IC2). The main thing to watch with the diodes and ICs is to orient them correctly, as shown on the overlay.

When these smaller parts have all been fitted, you'll find it quite easy to add the largest SMD component: L1. The leaded/through-hole parts can then be added, taking care to fit CON1 and CON2 so that their moulded spigots pass down through their corresponding holes, thereby ensuring that each connector sits flat against the PCB.

Note that you may need to enlarge the PCB holes to allow this and it may also be necessary to bend up the centre earthing pin of each socket to clear the top of the PCB.

When you're fitting the two LEDs, keep their leads quite straight and position each LED so that the underside of its body is 10mm above the top of the PCB. A 10mm-wide cardboard spacer inserted between their leads can be used to ensure that the LEDs are soldered in at the correct height.

Finally, the four interconnecting SIL headers can be added. These mount on the top of the PCB with their pins passing down through it and soldered underneath. Make sure you don't apply too much solder to the pins themselves though, because they will need to mate with the SIL sockets on each side of the Arduino board.

That completes the shield PCB assembly. It can now be placed to one side while you drill the metal box.

Preparing the box

There aren't very many holes to be drilled in the aluminium case – but they must be accurately positioned so that the PCB assembly will fit without problems. We've prepared a drilling and cutting template for the case and this diagram can be downloaded in PDF format from the *EPE* website and printed out. It can then be attached to the case and the holes drilled.

Note that it's best to use a small (eg, 1mm) pilot drill to start the holes to ensure accurate positioning. The 6.5mm and 12mm-diameter holes in one end of the box can be initially drilled out to 4mm and then carefully enlarged to size using a tapered reamer. The square cut-out at the other end of the box can be made by drilling a series of small holes around the inside perimeter, then knocking out the piece and filing the job to a smooth finish.

Mounting the modules

Once the box has been prepared, you're ready for the final assembly. This mainly involves mounting the two PCB modules on the inside of the box lid, but this needs to be done in a particular order.

Fig.5 shows how it all goes together. Just follow this assembly diagram and the internal photos and you shouldn't have any problems.

Begin by attaching M3 × 15mm tapped spacers to the two holes spaced 18mm apart at one end of the lid. These should be secured using M3 × 6mm machine screws, as shown in Fig.5.

That done, feed M3 × 10mm machine screws through the next pair of holes (spaced 28mm apart) and fit an M3 nylon hex nut on each of these screws. These nylon nuts act as short spacers, to position the Arduino PCB just clear of the lid.

Similarly, feed M3 × 20mm M3 machine screws through the final two holes in the lid (spaced 48mm apart) and fit these with M3 nylon hex nuts

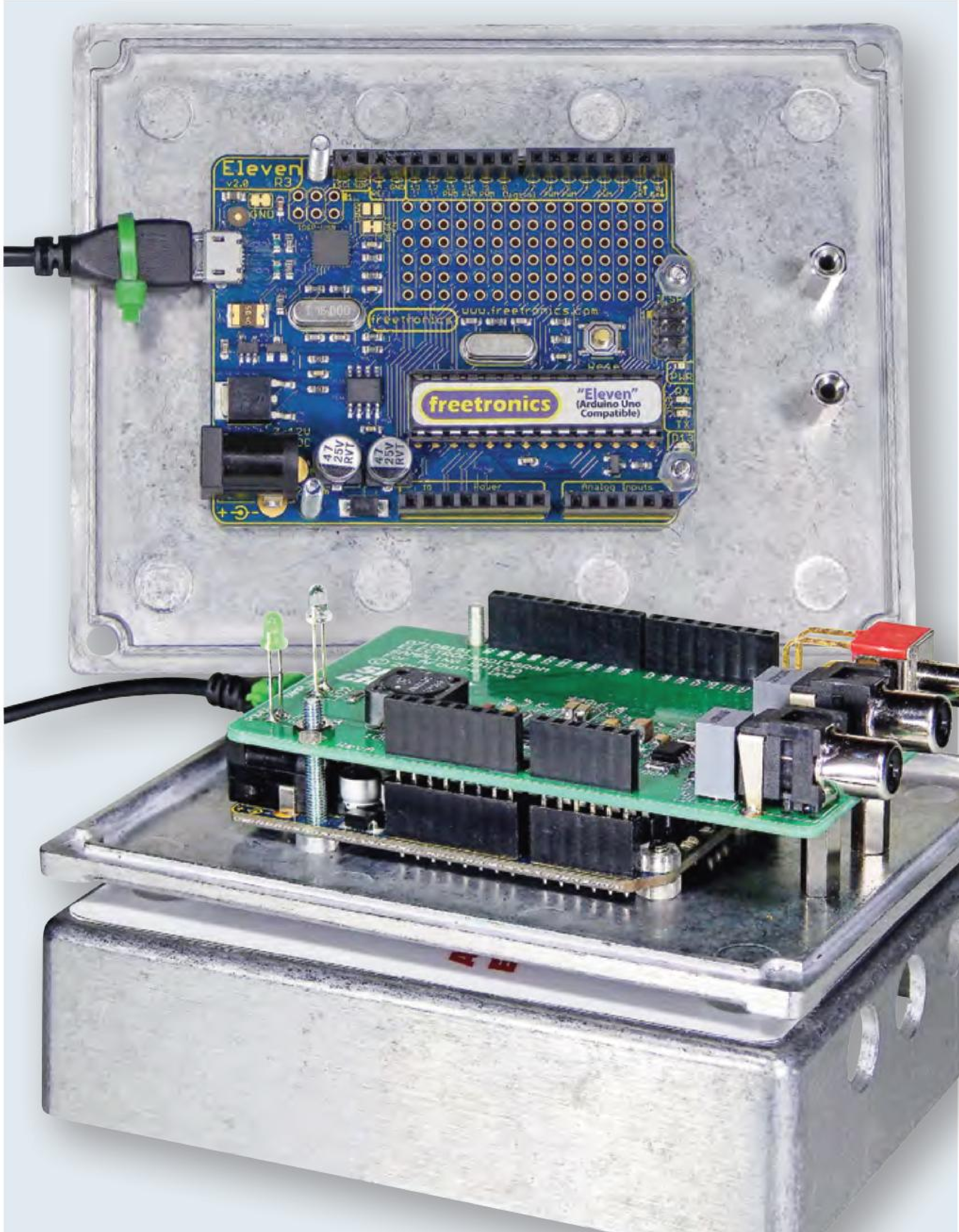


Fig.5: the photo at top shows the Arduino module (a Freetronics Eleven has been used) mounted on the case lid, while immediately above is the completed assembly with the shield board plugged in and secured in place.

as well, again to act as short spacers for the Arduino module.

The next step is to turn the Arduino module upside down and check that the mounting lugs on its 2.1mm power connector don't protrude down from the underside of the PCB by more than about 1.5mm. If they do, trim them back using a pair of sharp side cutters. This is necessary to ensure that they don't contact with the metal lid when the Arduino module is mounted in position.

Once that had been done, plug the USB cable's micro-B plug into the matching socket on the Arduino module. The module can then be fitted to the four mounting screws on the lid, so that it rests on the four nylon nut spacers. A pair of nylon nuts can then be fitted to the shorter mounting screws at one end of the module to secure it in place.

You won't be able to fit nuts on the two longer screws though, because there isn't room on the Arduino module for this to be done. Instead, this end of the assembly is secured later.

The next step is to plug the *ECG Sampler* Shield PCB into the Arduino board, as shown in Fig.5. Make sure that all the SIL header pins go into the SIL socket holes on the Arduino. Make sure also that the mounting holes at the 'LEDs end' of the shield PCB go over the two M3 × 20mm mounting screws.

Push the shield PCB down until its input end rests on the two 15mm spacers. The other end (the LEDs end) should rest on top of the 2.1mm DC power socket. Once it's in position, attach a pair of M3 hex nuts to the M3 × 20mm mounting screws, to hold both PCBs in place.

The final step is to use another pair of M3 × 6mm machine screws to fasten the input end of the shield PCB to the two M3 × 15mm spacers. **It's a good idea to fit a small star lockwasher under the screw between CON1 and CON2, to make sure that the screw makes a good electrical connection with the earth copper of the PCB.** This connection is used to connect the metal case to the PCB earth, for proper shielding. Both screws should be firmly tightened.

Final assembly

Once the lid assembly has been completed, it can be fitted into the case. That's done by first tilting it at an angle of about 20° at the RCA connector end, then lowering it into position so that the connectors and switch S1 pass through their respective holes in the case. The other end can then be lowered into position, at the same time making sure that the two LEDs on the shield PCB go through their 3.5mm holes in the base (which becomes the top). It's then simply a matter of screwing the cover and lid together using the four supplied countersunk-head M4 screws.

Front panel

The front panel artwork is available for download as a PDF file from the *EPE* website. You can then either print it out and hot-laminate it to protect against scratches and finger grease or you can print out a synthetic Dataflex or Datapol self-adhesive label (see above panel).

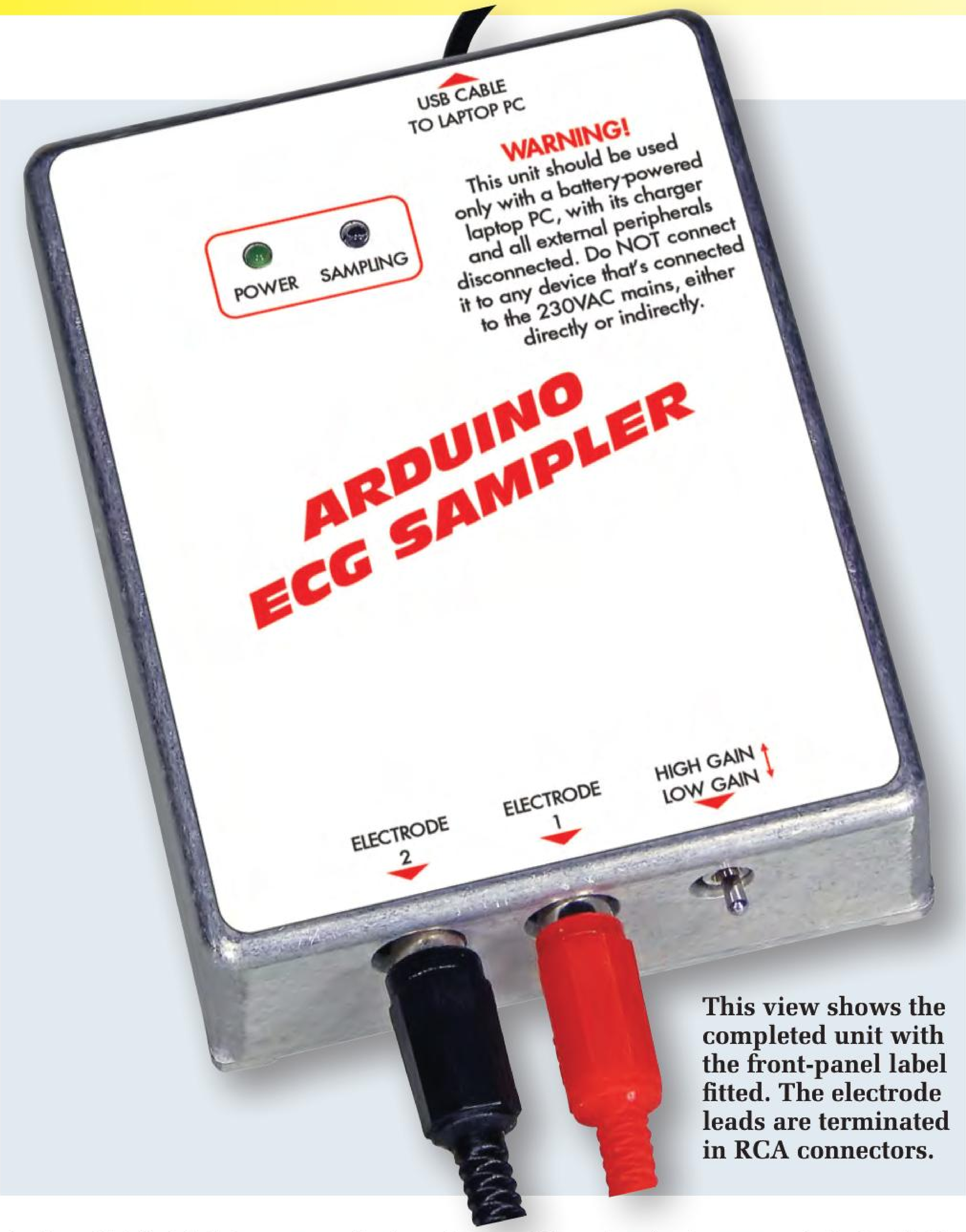
Datafelex/Datapol labels

(1) For Dataflex labels, go to: **www.blanklabels.com.au/index.php?main_page=product_info&cPath=49_60&products_id=335**

(2) For Datapol labels go to: **www.blanklabels.com.au/index.php?main_page=product_info&cPath=49_55&products_id=326**

Once you have the label, cut out the holes for the LEDs with a hobby knife and then attach it to the case. You can attach a laminated label using either double-sided tape or silicone adhesive.

It's also a good idea to fit four small self-adhesive rubber or plastic feet to


USB CABLE
TO LAPTOP PC
WARNING!
This unit should be used only with a battery-powered laptop PC, with its charger and all external peripherals disconnected. Do NOT connect it to any device that's connected to the 230VAC mains, either directly or indirectly.
POWER
SAMPLING
ARDUINO
ECG SAMPLER
ELECTRODE 2
ELECTRODE 1
HIGH GAIN
LOW GAIN

This view shows the completed unit with the front-panel label fitted. The electrode leads are terminated in RCA connectors.

the box lid (which becomes the base), so that the heads of the PCB mounting screws cannot scratch any surface the unit is placed on.

Electrode leads

Although it's easy to obtain commercial ECG electrodes at relatively low cost, this doesn't seem to be the case with electrode leads. So regardless of which type of electrodes you use, the simplest approach is to make up a pair of leads yourself.

For this, we suggest you use a 3m length of reasonable-quality figure-8 stereo audio cable – the kind with a decent earth braid around each of the two centre conductors. Don't use 'el cheapo' ready-made stereo leads, because many of them don't provide adequate shielding.

The first step is to split the figure-8 cable apart over a distance of about 120mm at one end and fit each lead with an insulated RCA plug. The other end of the cable is then split over a distance of about 1.5m and the leads connected to the ECG electrodes.

The simplest approach is to fit the electrode ends of the cable with small insulated crocodile clips. That's because this type of clip is the easiest way to connect commercial ECG electrodes, which all seem to be fitted with a small metal contact stud. Presumably, commercial electrode leads have a matching clip for these studs but small crocodile clips make a good substitute.

When you're fitting these clips to the lead ends, strip back the cable's outer sleeve and the earth braid wires by about 15mm from the end, then fit a 25mm length of heatshrink sleeving so that the shield braid cannot make contact with anything. Only the centre conductor is soldered to the rear of the crocodile clip and you will need to remove not more than 5mm of the inner dielectric insulation before doing this.

The electrodes

Although you can use the adhesive electrode pads sold in pharmacies for use with TENS machines, these are generally rather expensive. Adhesive ECG electrode pads are also available via a number of suppliers on eBay and these come at a much more reasonable cost. However, when we tried these electrodes, they didn't seem to give a reliable low-resistance skin connection, resulting in a surprisingly high level of hum pick-up.

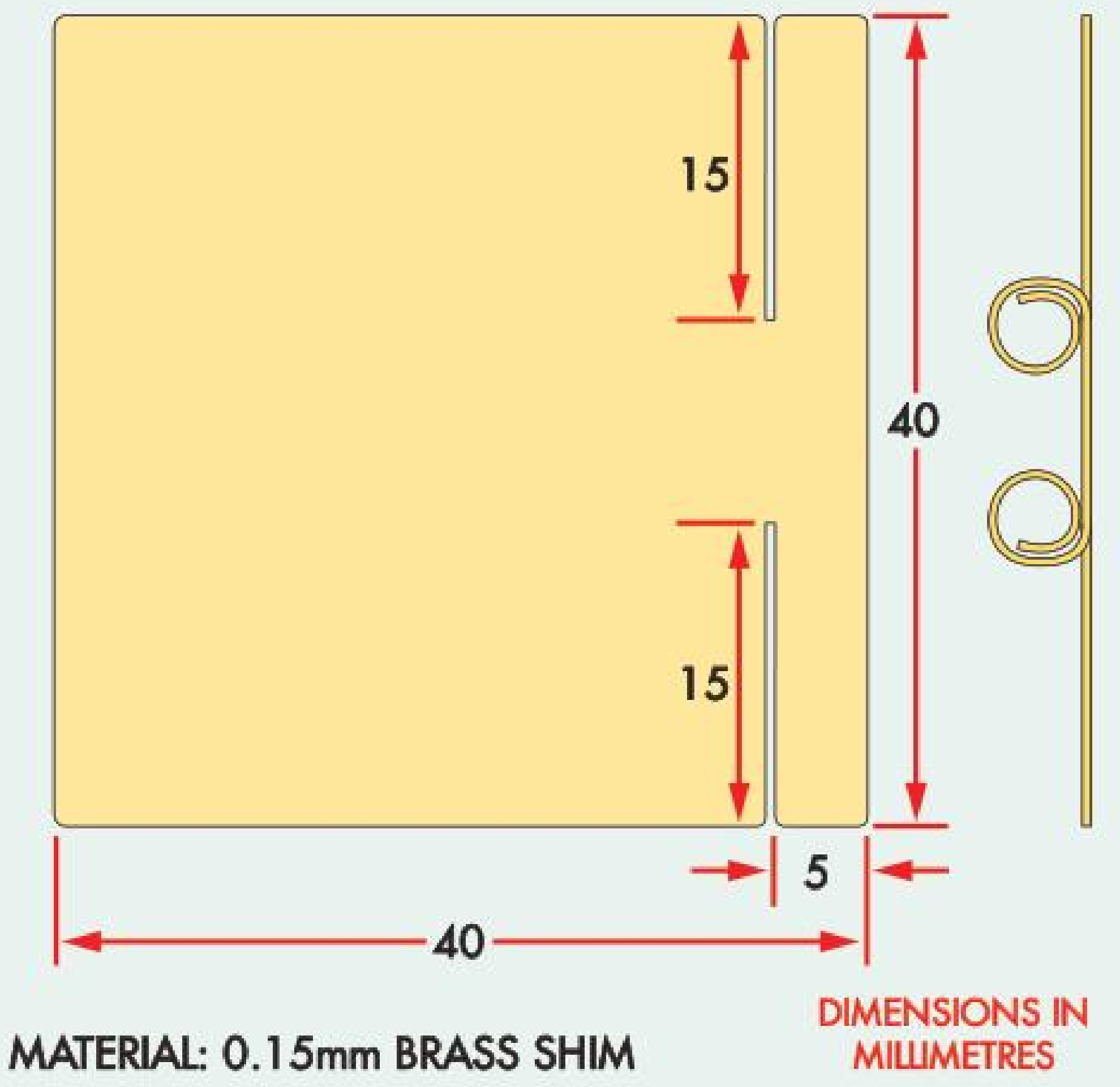


Fig.6: the electrodes are made using 40 × 40mm pieces of 0.15mm-thick brass shim (see text).

In practice, we found we could get much better results using a pair of home-made electrodes, each made from a 40 × 40mm piece of 0.15mm brass shim. Fig.6 shows the details. Use tin snips to trim the shims to size, then make two 15mm-long cuts along one side, leaving a 10mm space between the two cuts in the centre.

Next, bend the two ends of the 15 x 5mm strips up and towards each other, to form a pair of loops, as shown in the diagram. These loops then make convenient attachment points for the alligator clip at the end of each lead.

Before they're used, be sure to snip off each corner and smooth the edges with a small file and/or fine sandpaper, so they won't scratch the skin. And that's it – they are simple to make and they work extremely well.

Before each electrode is applied to an ankle or wrist, or any other part of the human anatomy, both the underside of the electrode and the surface of the skin should be well moistened with saline solution, to ensure that a good low-resistance contact is made. If you don't do this, you'll see a lot of hum in the ECG traces.

So how do you hold the electrodes firmly (but not-too-firmly) against the subject's skin? The answer is two simple adjustable straps, each made from a 250mm length of 20mm wide Velcro felt strip, along with a 50mm length of

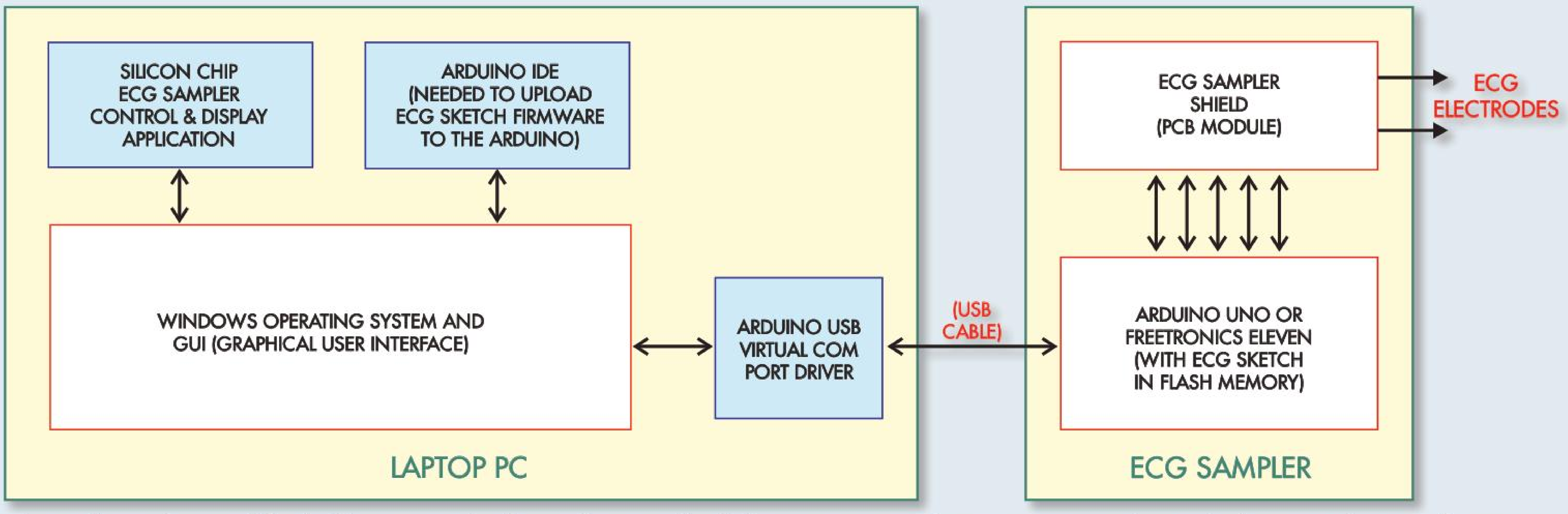

SILICON CHIP ECG SAMPLER CONTROL & DISPLAY APPLICATION
ARDUINO IDE (NEEDED TO UPLOAD ECG SKETCH FIRMWARE TO THE ARDUINO)
WINDOWS OPERATING SYSTEM AND GUI (GRAPHICAL USER INTERFACE)
ARDUINO USB VIRTUAL COM PORT DRIVER
LAPTOP PC
(USB CABLE)
ECG SAMPLER SHIELD (PCB MODULE)
ECG ELECTRODES
ARDUINO UNO OR FREETRONICS ELEVEN (WITH ECG SKETCH IN FLASH MEMORY)
ECG SAMPLER

Fig.7: the software block diagram. The large box on the left represents a laptop PC running Windows XP/SP3 or later, while the *ECG Sampler* unit is shown at right. Follow the instructions in the text to install the software.

the matching hook-strip affixed to the back of one end of each strip.

In practice, each strap is run around the subject's forearm or ankle and over its electrode, before being pulled reasonably tight to hold the electrode in place. It's simple, but it works surprisingly well.

Installing the software

As mentioned earlier, there are a number of software items that need to be installed on your laptop in order to use it to take ECG samples. In addition, a software 'sketch' has to be uploaded to the Arduino in the *ECG Sampler* so that it can carry out its tasks.

Fig.7 shows the software block diagram. The large box on the left represents a laptop PC, with its Windows XP/SP3 or later operating system and GUI shown at lower left. The *ECG Sampler* is shown on the right, linked to the laptop via a USB cable.

The *ECG Sampler* application (upper left of Fig.7) needs to be installed on the laptop, together with a virtual COM port driver (lower right, in the PC box) to allow it to communicate with the Arduino module. These are the two main items of software required in the laptop for the *ECG Sampler* to run.

However, there's another item of software which needs to be installed on your laptop, at least temporarily: the Arduino IDE. This is needed so that you can upload the *ECG Sampler* sketch to the Arduino.

We suggest you download and install this software in the following order:

1) Download the Arduino IDE

Go to the main Arduino website at: **www.arduino.cc/en/Main/Software**. We used the **1.6.5-r2-windows.exe** version of the IDE but there may be a later version available by the time you read this. There's also a zipped-up version.

When you download and install the Arduino IDE, it comes with a USB virtual COM port driver to suit the Arduino Uno. This is installed in the ***/Drivers*** folder of the IDE installation. As a result, if you are using an Arduino Uno in your *ECG Sampler*, you'll already have its matching USB port driver.

Alternatively, if you're using a Freetronics Eleven, you will have to download the matching USB driver from: **www.freetronics.com.au**

At the time of writing, this was in a zip file named **FreetronicsUSBDrivers_v2.2.zip**. After downloading it, unzip it into a folder so that it's ready for installation – see below.

2) Plug in the cable

Connect your *ECG Sampler* to a USB port on your laptop. The *ECG Sampler's* power LED should immediately light but the Windows OS will probably flag a problem, indicating an error when it tried to install the driver for this 'new and unknown' device. Even if this doesn't happen, you still have to install the correct driver.

3) Go to Control Panel

Next, open Device Manager, which will show an error icon alongside an 'Unknown device' listing. If you right-click this item and open Properties, you'll see that the problem lies with the driver for the device – it's either not properly working or not installed at all.

SAFETY WARNING

To ensure complete safety, this *ECG Sampler* should be used only with a battery-powered laptop PC; ie, one that's NOT connected to the mains via its charger. You should also disconnect all external cable connections to the laptop, eg, printers and network cables.

Do NOT use it with a desktop or laptop PC that's connected to the 230V AC mains, either directly or indirectly.

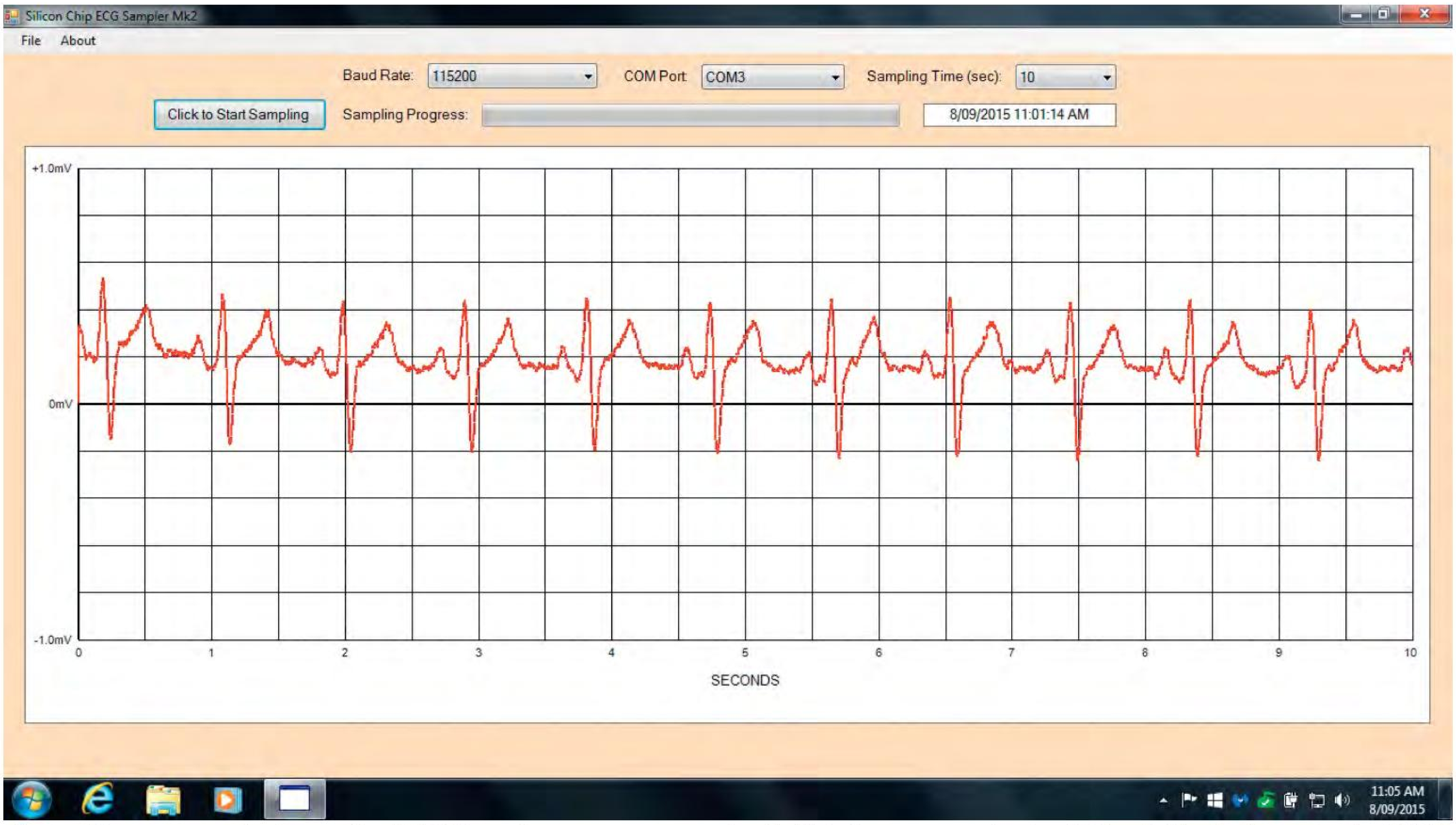
These precautions are necessary to eliminate the remote possibility that a fault in the power supply of a mains-powered device could result in a high AC voltage being applied to the electrodes.

To install the driver, click on the 'Driver' tab, select 'Update Driver' and then click 'Browse my computer for driver software'. You then browse to either the **/Drivers** folder of your Arduino IDE installation (to get Arduino's Uno driver) or to the folder where you unzipped the Freetronics driver (to get the Freetronics Eleven driver).

In either case, you should be able to see the **.inf** file that Windows needs to install the new USB driver. When you return to the Device Manager, Windows should be able to install the driver and you should then see the 'This device is working properly' message.

4) Open your web browser

Go to **www.epemag.com** and download both the Windows software for the *ECG Sampler* (**SiliconChipECGSamplerMk2.zip**) and the matching Arduino firmware sketch (**sketch_for_ECGSampler.ino**). These files should



Baud Rate: 115200

COM Port: COM3

Sampling Time (sec): 10

8/09/2015 11:01:14 AM

Fig.8: this screen grab shows the *ECG Sampler* program running in Windows 7 on a laptop PC and displaying a typical ECG waveform. The tiny regular oscillatory noise component in each cycle is residual 50Hz hum.

be saved in your ***/Documents*** folder, in a sub-folder called ***/Arduino sketches***.

5) Launch the Arduino IDE

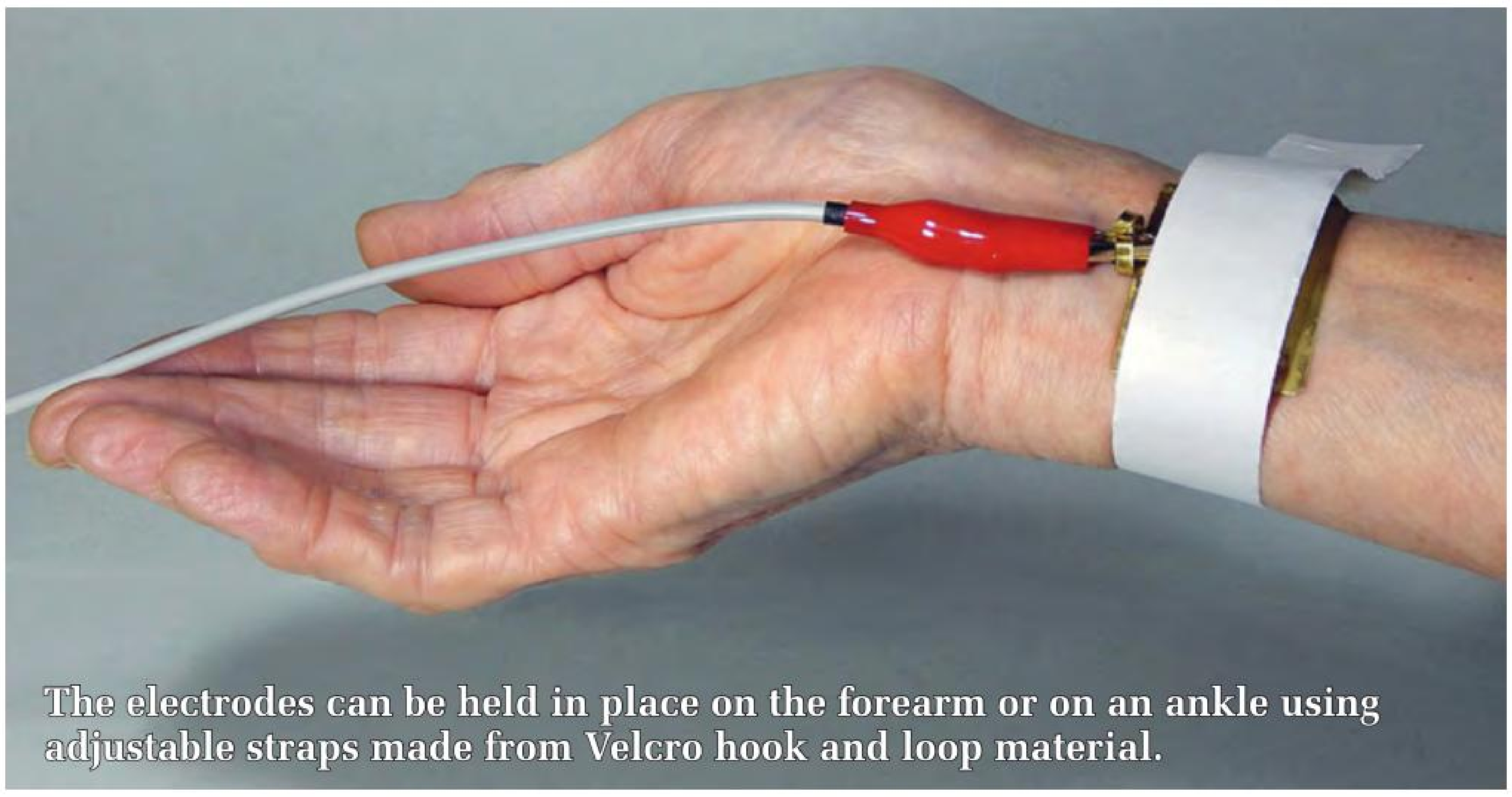
Direct it to that sub-folder to find the sketch. Open this and upload it to the flash memory in your *ECG Sampler's* Arduino (you'll find this process is quite straightforward).

6) Final stage

Unzip the **SiliconChipECGSampler-Setup.zip** file and double-click the **.msi** file to install our Windows *ECG Sampler* application. That's it – you should now be ready to roll with your new *ECG Sampler*.

Taking an ECG

Apart from the *ECG Sampler's* gain switch, which is set to either LOW (1000) or HIGH (2000), all functions of the USB/*ECG Sampler* are controlled using the *ECG Sampler* program. This is easy to use because when you fire it up, it provides a GUI window (see Fig.8) which provides combo-box buttons along the top so you can set the sampling configuration: the Baud rate to be used (115,200) for communication with the *Sampler*, the COM port it's connected to (usually either COM3 or COM4) and the sampling time you want (5, 10 or 20 seconds).



The electrodes can be held in place on the forearm or on an ankle using adjustable straps made from Velcro hook and loop material.

You then start an ECG recording simply by clicking on the 'Start Sampling' button. The software then shows a progress bar at the top of the application window and a sample plot display which 'grows' in the accompanying graph graticule.

As shown on Fig.8, there are two drop-down menus at the top, with the familiar labels 'File' and 'About'. The first menu gives you options for saving, reloading and printing your ECG recordings, plus an option to close the application when you're finished. The 'About' menu item simply brings up a small dialog box which shows the version number of the software.

Lead configurations

Finally, which lead configuration should you use, just to take a basic look at your own ECG or that of someone else?

Our recommendation is that you use the 'Lead II' limb configuration, with lead 1 connected to the subject's left ankle and lead 2 connected to their right wrist or inside forearm. This usually gives the largest waveform amplitude, providing your electrode-skin connections are good.

If you get weak waveforms with a relatively large amount of hum, this is

Parts List

1 PCB, available from the *EPE PCB Service*, coded 07108151, 93 × 53mm
1 set of Arduino stackable shield headers (1 × 10 pin, 2 × 8 pin, 1 × 6 pin)
1 diecast aluminium box, 119 × 93 × 34mm
1 Arduino Uno or Freetronics Eleven module
1 USB cable, type A to micro-B connectors
2 RCA sockets, PCB-mount (CON1, CON2)
1 100µH 1.6A SMD inductor (L1), Murata 48101SC (Element14 2112367)
1 miniature DPDT toggle switch, PCB-mount (S1)
2 M3 × 15mm tapped spacers
4 M3 × 6mm machine screws (round head)
2 M3 × 10mm machine screws (round head)
2 M3 × 20mm machine screws (round head)
6 M3 nylon hex nuts
1 M3 metal hex nut
4 adhesive rubber/plastic mounting feet, small

ECG electrode parts
2 insulated RCA plugs
3 metres of figure-8 shielded stereo cable
2 40 × 40mm squares of 0.15mm brass shim (see text)
2 32mm insulated alligator clips (one red, one black)
2 50mm lengths of 20mm wide Velcro hook strip
2 250mm lengths of 20mm wide Velcro felt strip
2 25mm lengths of 4mm diameter heatshrink sleeving

Semiconductors
1 AD623ARZ instrumentation op amp, SOIC-8 package (IC1)
1 NE5532D dual op-amp, SOIC-8 package (IC2)
1 3mm green LED (LED1)
1 3mm red LED (LED2)
2 1N5711W7F Schottky diodes, SOD-123 package (D1,D2)

Capacitors (1206 SMD)
4 100µF 6.3V X5R ceramic
1 10µF 6.3V X5R ceramic
1 6.8µF 16V X7R ceramic
2 1.0µF 5% 100V MKT (leaded)
2 1.0µF 16V X7R ceramic
3 100nF 16V X7R ceramic
1 47nF 50V X7R ceramic
2 1nF 1% 50V C0G ceramic

Resistors (0.125W, 1%, 1206 SMD)
2 2.2MΩ
2 20kΩ
1 11kΩ
1 10kΩ
2 4.7kΩ 0.1%
2 3.0kΩ
1 2.7kΩ
1 2.2kΩ
1 1.2kΩ
2 470Ω
1 100Ω
1 82Ω

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usually a sign of poor electrode contact. So take them off, apply a bit more saline solution and try again.

The exact positioning of the limb electrodes is not critical, as the limbs are really just being used as convenient conductors joined to the four 'corners' of the subject's trunk. The most important thing is to get the best possible contact to the skin.

If you want to try some of the chest positions for the lead 1 electrode, the electrode positions are then fairly critical. You really need to have some medical background to know the right chest electrode positions, so it's best to leave this to the professionals.

Note that if lead 1 is used with a chest electrode, lead 2 should be connected to electrodes in all three of the limb positions so that it provides a 'whole body' reference signal. In practice, this means that you'll need to make up at least two more electrodes and connect them in parallel with the original lead 2 electrode. That's done by connecting the additional electrodes to the *ECG Sampler's* CON2 input socket via leads that are the same lengths as the original leads.

If you really want to play around with all the lead configurations, you might want to make up a set of nine electrodes and leads, plus a small switch box to allow you to select any of the standard lead configurations (see diagram in the *Your heart and its electrical activity* box) at will.

PoLabs
For more information or
software download please visit
www.poscope.com/epe
PoKeys
Connect, Control
- USB
- Ethernet
- Web server
- Modbus
- CNC (Mach3/4)
- IO
- PWM
- Encoders
- LCD
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- Compact PLC
Stepper motor drivers
Drive
- up to 256 microsteps
- 50 V / 6 A
- USB configuration
- Isolated
- up to 32 microsteps
- 30 V / 2.5 A
PoScope Mega1+
PoScope Mega50
Measure
- up to 50MS/s
- resolution up to 12bit
- Lowest power consumption
- Smallest and lightest
- 7 in 1: Oscilloscope, FFT, X/Y, Recorder, Logic Analyzer, Protocol decoder, Signal generator

Win a Microchip 2D/3D Touch & Gesture Development Kit

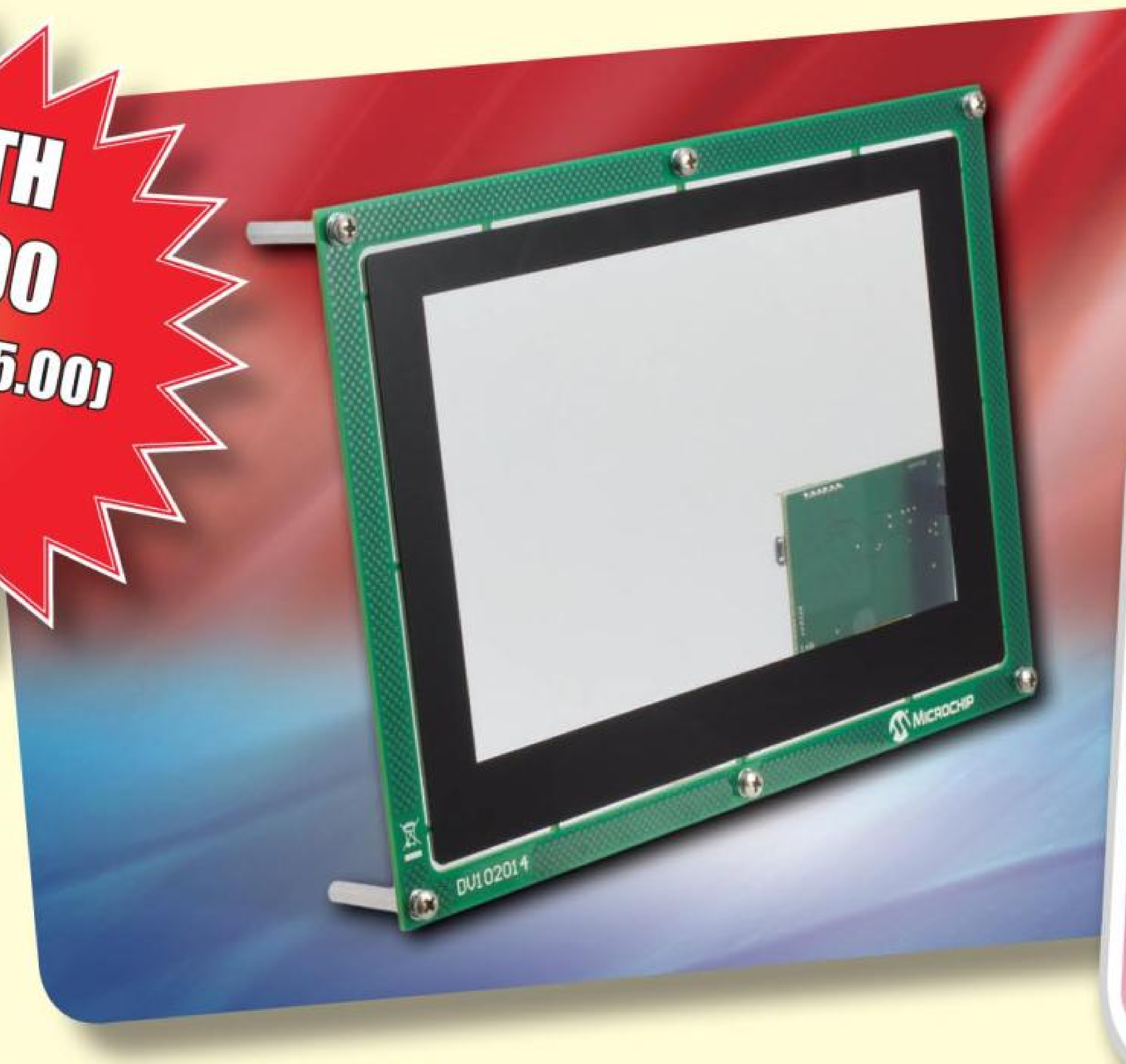
EVERYDAY PRACTICAL ELECTRONICS is offering its readers the chance to win a 2D/3D Touch and Gesture Development Kit (DV102014) from Microchip. The 2D/3D Touch and Gesture Development Kit the industry's first development kit for integrated 2D projective-capacitive touch (PCAP) and 3D gesture recognition on displays.

The kit will provide designers with easy access to Microchip's patented 2D and 3D GestIC® sensing technology, allowing them to easily integrate 2D multi-touch and 3D hand-gesture recognition into their display applications. The use of electric-field-based technology now enables hand and finger gestures to be tracked both on the display surface as well as above at a distance of up to 20cm. In addition, the development kit provides an easy-to-use, 'out-of-the-box' experience that requires no code development. Parameterisation, diagnostics and optional settings are done through Aurea 2.0, a free downloadable graphical user interface (GUI).

The 2D/3D Touch and Gesture Development Kit features Microchip's latest PCAP controller, the MTCH6303, with the MGC3130 3D gesture controller. It includes an eight-inch transparent touch sensor to enable rapid prototyping for widely available displays. The MTCH6303 provides multi-touch coordinates with a five-finger scan rate of 100 Hz. In addition, it has an integrated multi-finger surface gesture suite which makes it a good fit both for operating system (OS) driven applications as well as embedded systems without an operating system.

The MGC3130 with Microchip's award-winning GestIC technology was the first electrical-field-based 3D gesture controller to offer low-power, precise and robust hand-position tracking at 200Hz. In addition, GestIC technology uses advanced Hidden Markov Models to ensure that the recognition rate for 3D hand gestures is above 95%. Free-space hand gestures are universal, hygienic and easy to learn, making them ideal for display applications.

WORTH
$249.00
(approx. £195.00)
EACH



June 2016 ISSUE WINNER

Peter Collins, who works at Parkinson Harness Tech Ltd, Boston, Lincolnshire

Anthony Hubbard, who works at TUV-SUD Product Service Ltd, Fareham, Hampshire

Bryan Hunter, who works at BH Electronics, Dundee

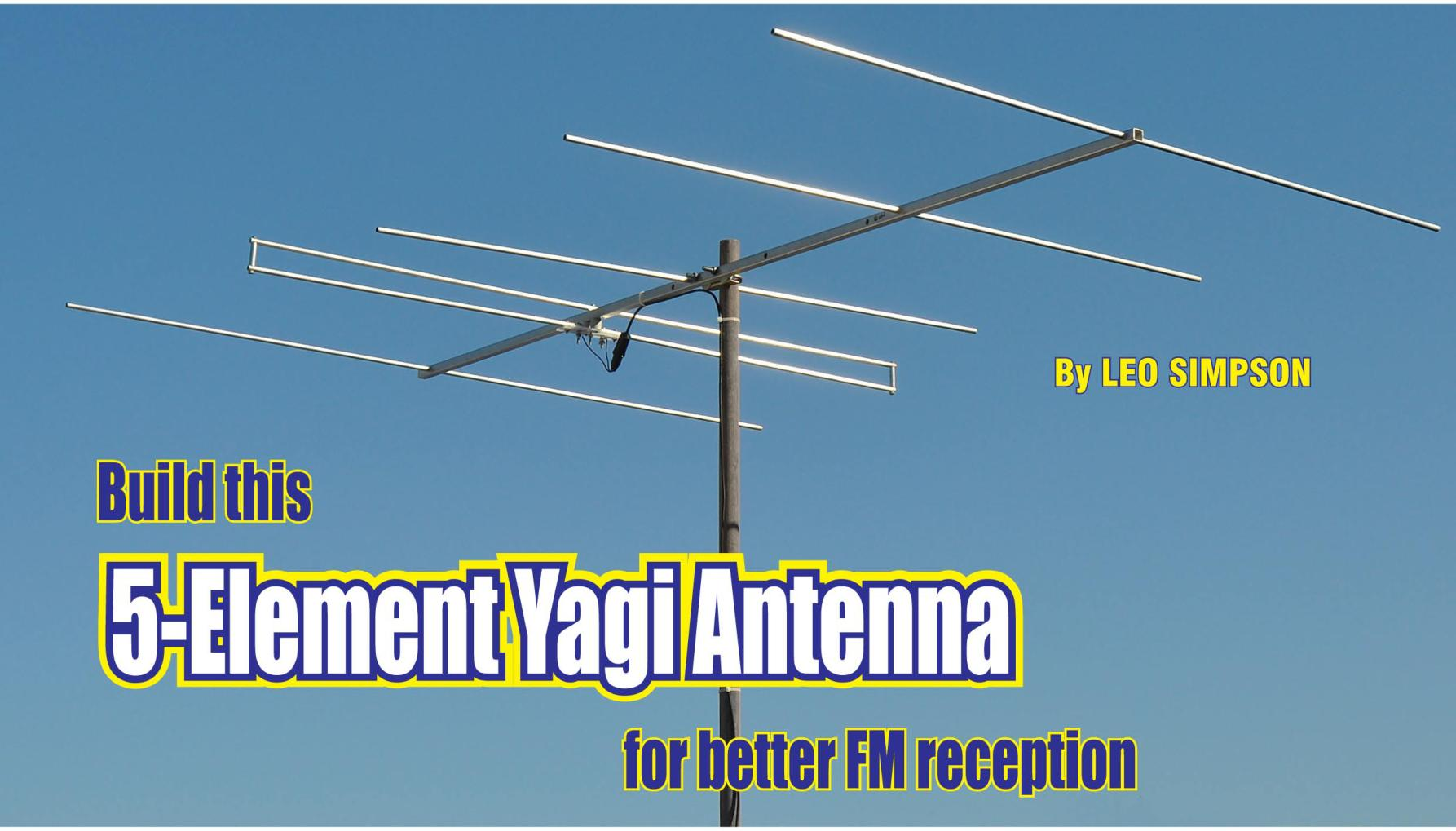
They all won a Microchip PICkit 3 Debug Express Kit, valued at £48.65

HOW TO ENTER

For your chance to win a 2D/3D Touch and Gesture Development Kit, visit: **www.microchip-comps.com/epe-sept16** and enter your details in the online entry form.

CLOSING DATE

The closing date for this offer is 31 October 2016.



By LEO SIMPSON

Build this
5-Element Yagi Antenna
for better FM reception

What's your FM reception like? Pretty poor? Does the music sound distorted or are there lots of sibilants on voice? If so, you need a proper FM antenna, not a bit of wire hanging out the back of your tuner. But, they're not that easy to buy these days! So why not build your own? This *5-element Yagi Antenna* is designed specifically for the FM band. You'll be amazed at how good those stations can sound when they have a strong signal.

These days, many people are listening to DAB/DAB+ broadcasts (mostly DAB in the UK) and we can well understand why. There are more stations and provided the signal is OK, the sound will be OK too. But it will only be 'OK' to the extent that the sampling rates used by virtually all DAB/DAB+ stations are barely adequate to give good sound quality.

Yes, yes, we know that many people are now listening to Internet streaming services and they have thousands of music stations from around the world to choose from, but again, the sound quality is just average.

If you want really good broadcast sound quality, FM stations cannot be bettered. Of course, if you live outside the DAB/DAB+ coverage zones, then it's FM or nothing if you want to listen to music broadcasts with good sound quality.

And, if you *are* in a remote area, then you are going to need a good FM antenna to get the best sound quality – nothing else will do. Of course, living in a large city, probably with hilly surrounds and tall buildings can still mean that you will get weak signals and 'multipath' reception.

This is the same effect as 'ghosting' on TV. Multipath causes bad distortion and you can only cure it with a high-quality antenna.

So what FM antenna should you buy? They are virtually unavailable. This was the situation when I originally designed this antenna decades ago. Needless to say, things have not improved since then, and I still get asked for a good FM antenna.

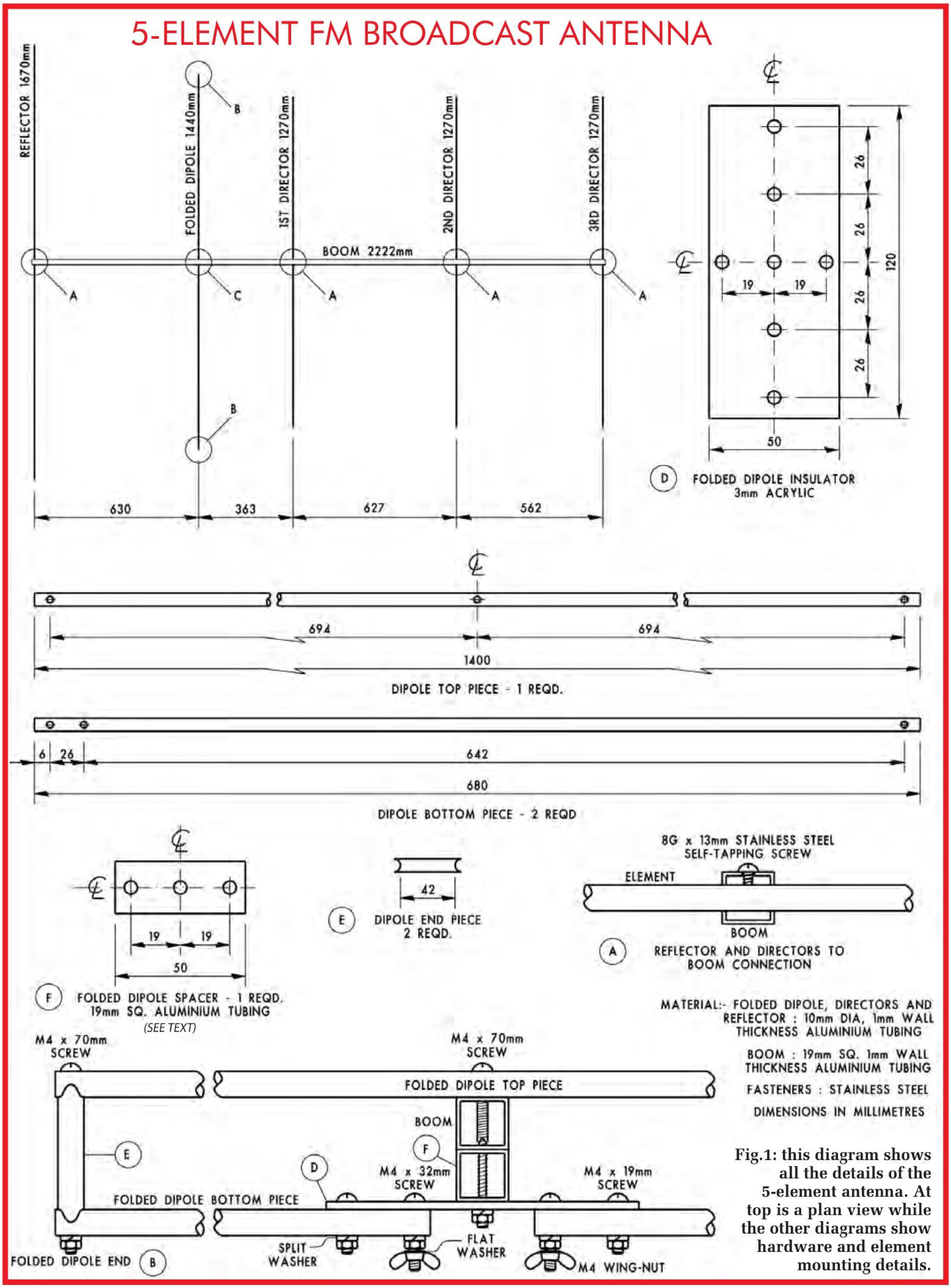
The result is shown here – my latest version of an old classic. I've tweaked it with some slight changes, but it is essentially a tried-and tested-design that will help you get the best performance from your tuner.

The antenna is a 5-element Yagi array. It has a folded dipole, a single reflector and three directors. It has an estimated gain of between +8dB and +9dB with respect to a dipole and an improved front-to-back ratio compared to a 3-element array, the most common FM antenna in the past.

By the way, if you have an old VHF TV log periodic array it *could* be pressed into service, but it won't perform quite as well as this antenna, which is cut to suit just the FM band from 88 to 108MHz.

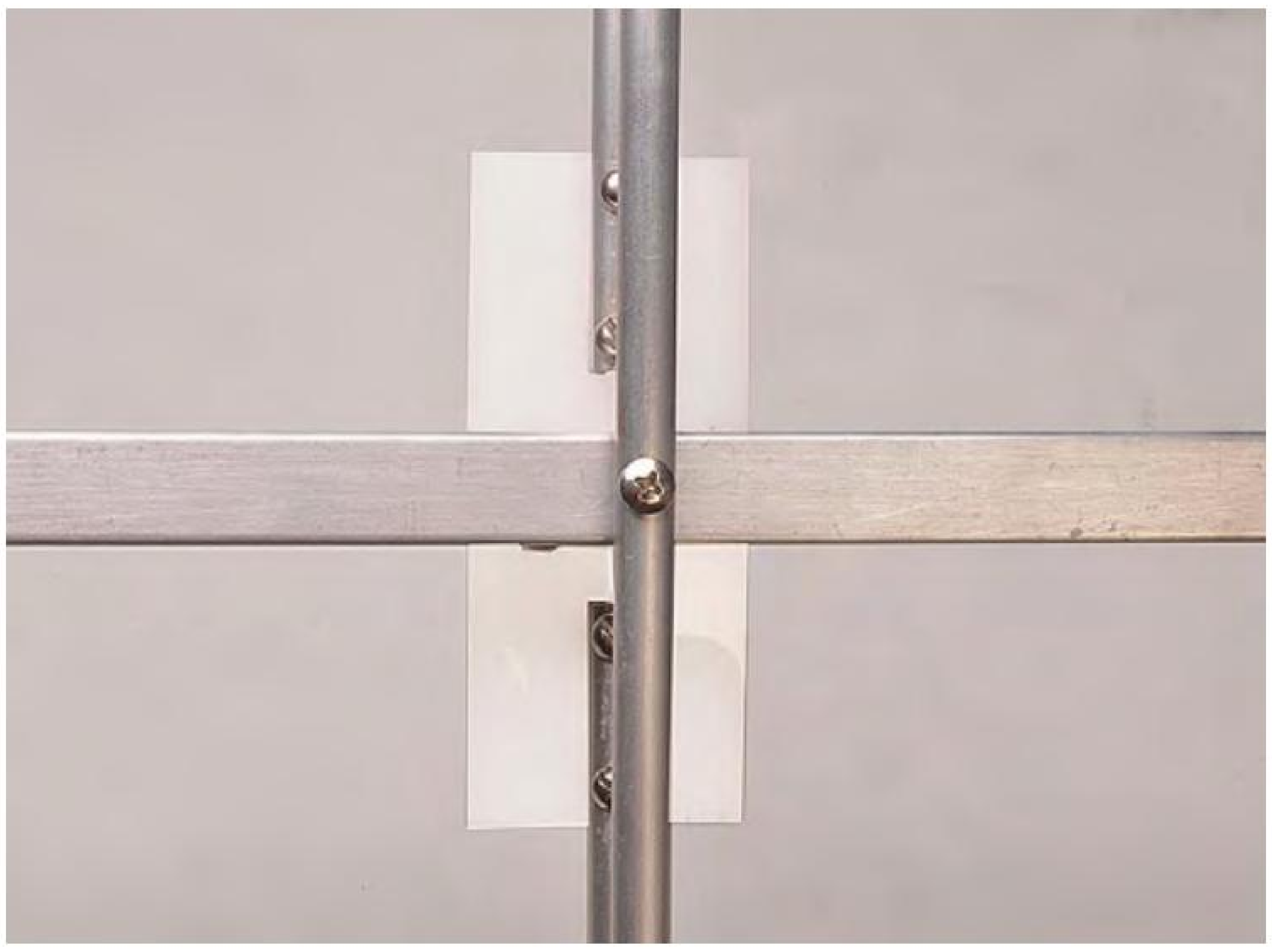
Narrow acceptance angle

As well as a good front-to-back ratio, this antenna is also quite directional – or to put it another way, it has a narrow acceptance angle. Both of these factors mean that reflected

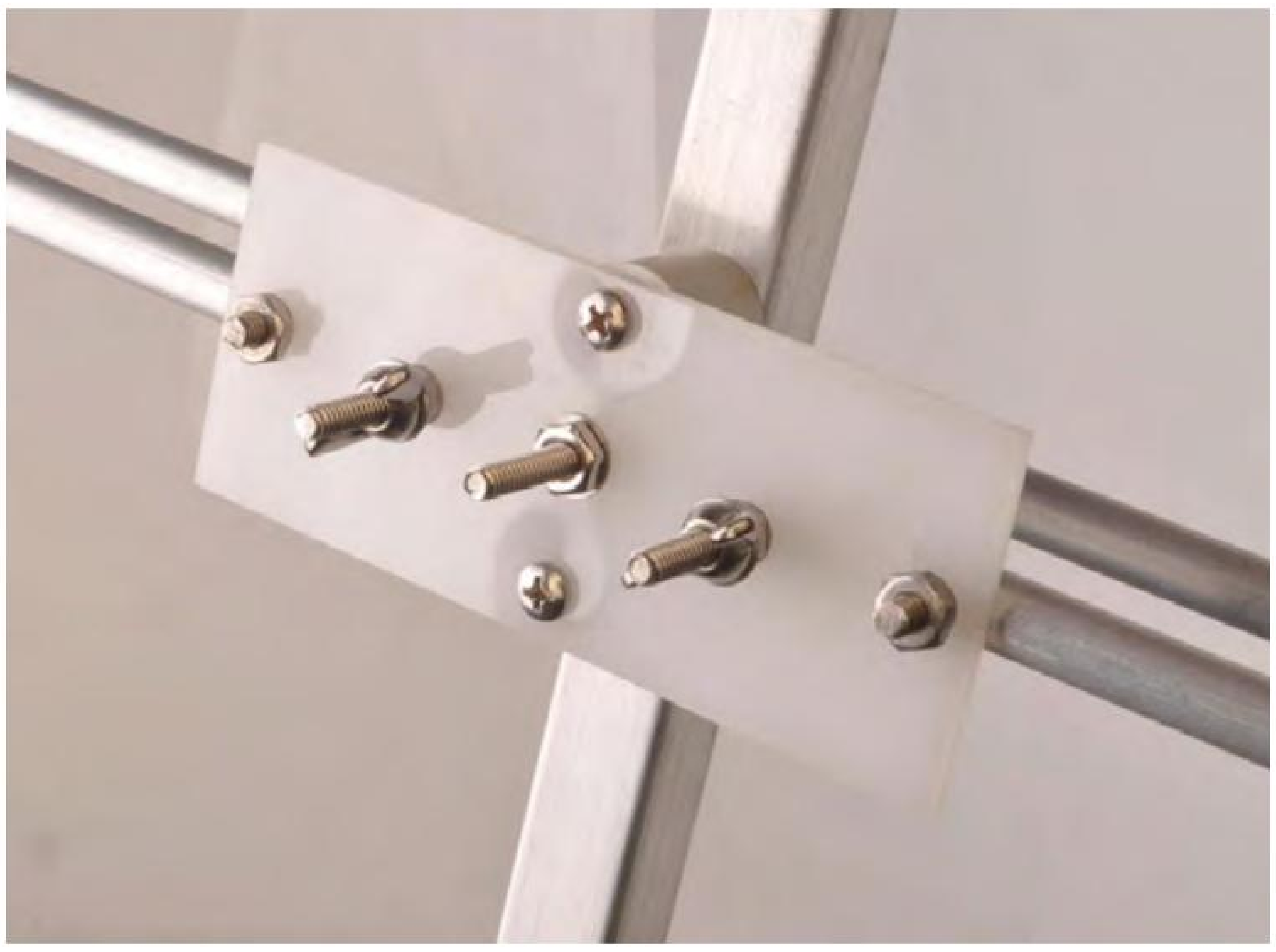


5-ELEMENT FM BROADCAST ANTENNA
REFLECTOR 1670mm
FOLDED DIPOLE 1440mm
1ST DIRECTOR 1270mm
2ND DIRECTOR 1270mm
3RD DIRECTOR 1270mm
BOOM 2222mm
A
B
C
630
363
627
562
26
120
19
50
D FOLDED DIPOLE INSULATOR 3mm ACRYLIC
694
1400
DIPOLE TOP PIECE - 1 REQD.
6
642
680
DIPOLE BOTTOM PIECE - 2 REQD
42
E DIPOLE END PIECE 2 REQD.
8G x 13mm STAINLESS STEEL SELF-TAPPING SCREW
ELEMENT
BOOM
A REFLECTOR AND DIRECTORS TO BOOM CONNECTION
F FOLDED DIPOLE SPACER - 1 REQD. 19mm SQ. ALUMINIUM TUBING
(SEE TEXT)
MATERIAL:- FOLDED DIPOLE, DIRECTORS AND REFLECTOR : 10mm DIA, 1mm WALL THICKNESS ALUMINIUM TUBING
BOOM : 19mm SQ. 1mm WALL THICKNESS ALUMINIUM TUBING
FASTENERS : STAINLESS STEEL
DIMENSIONS IN MILLIMETRES
M4 x 70mm SCREW
FOLDED DIPOLE TOP PIECE
M4 x 32mm SCREW
M4 x 19mm SCREW
FOLDED DIPOLE BOTTOM PIECE
SPLIT WASHER
FLAT WASHER
M4 WING-NUT
FOLDED DIPOLE END B

Fig.1: this diagram shows all the details of the 5-element antenna. At top is a plan view while the other diagrams show hardware and element mounting details.



This shot shows the fixing of the dipole top element to the boom and plate. This is done with a 70mm-long stainless steel screw which passes through the top element, then the boom and spacers below to the Lexan plate.



The dipole insulator plate has wing nut terminals to connect 300Ω ribbon or a 300Ω-to-75Ω balun. The plate is made from Perspex, Lexan or other acrylic material. The square boom makes mounting easy.

signals coming in from the sides and rear of the antenna will be suppressed. This is worthwhile because the more suppression you can obtain for reflected signals, the less distorted the resulting stereo sound will be.

We're talking here about 'multi-path' reception, which used to plague analogue TV reception and cause ghosts in the picture. With FM broadcasts, multi-path reception causes the sound to spit and sputter, especially if a low-flying plane passes overhead.

Apart from reducing multipath problems, the big reason to build this antenna is to obtain lots more signal than you would get from a random piece of wire or the common twin-lead dipole wire antenna that is supplied with many tuners. Furthermore, because it will be installed outside your home, the signal pickup will be even better. In fact, our observations show that with a good FM antenna such as this, it is possible to pick up stations (in stereo) which may be more than 160km away.

Finally, by feeding more signal to your tuner, even from your strong local stations, you will improve the reception and it will be less susceptible to interference from equipment with switchmode power supplies. There will be less distortion, better separation between channels and less hiss in the background.

Tools you will need

Most enthusiasts will have all the tools needed for this project: a hacksaw, electric drill and a vice. It would also help if you have a drill press, but you can do without this. You will also find that a tube cutter (as used by plumbers) will be good for making clean cuts on aluminium tubing. Apart from an antenna clamp (U-bolt and V-block bracket), no special hardware or fittings are required.

Making this antenna is quite straightforward. If you have all the materials available you can probably do it in a couple of afternoons.

Fig.1 shows all the details of the 5-element antenna. It shows the dimensions of all the elements and the various hardware bits you will have to make to assemble the antenna. At the top is a plan view showing the length of all five elements and their spacing along the boom.

Screws and nuts

After a few years' exposure to the elements, many antennas are in a poor state. Aluminium may not 'rust' but it does oxidise, particularly in seaside areas or in metropolitan areas where there is a lot of industrial fallout. Corrosion will also be a lot worse if you don't use the right screws and nuts.

We strongly recommend the use of stainless steel screws, nuts and washers throughout, whether for machine screws or self-tappers. They do cost a little more, but they last indefinitely. You will find a good array of stainless steel screws and fittings available from ships' chandlers.

Don't, on any account, use brass screws. When used to attach aluminium elements these will corrode away almost before your eyes. Nor do we recommend galvanised, bright zinc or cadmium plated steel screws. In seaside areas these can be visibly corroded with just a few days' exposure.

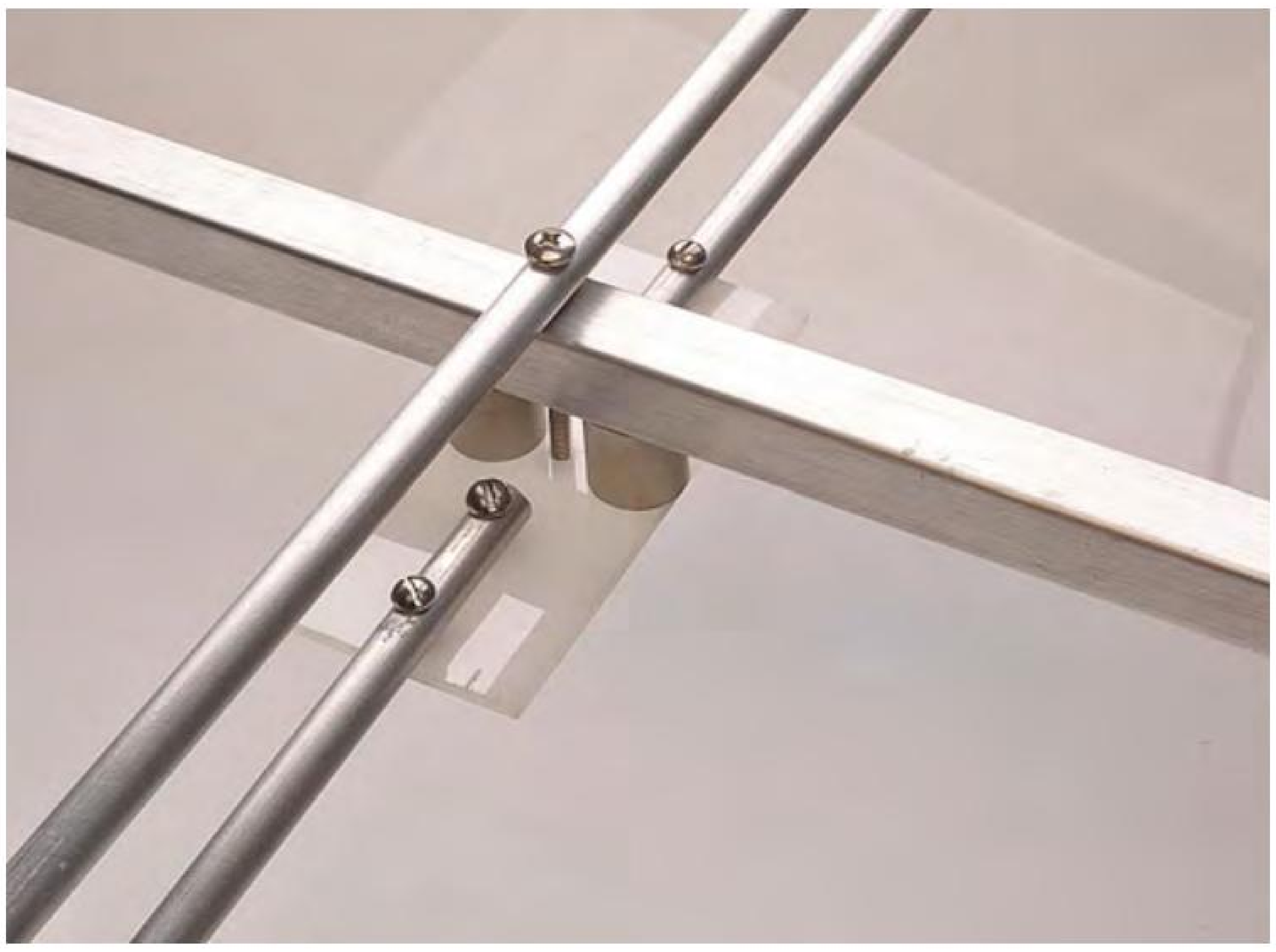
In rural areas, away from the sea or city pollution, you can probably get away with galvanised screws but the antenna will last longer if you paint it.

Starting work

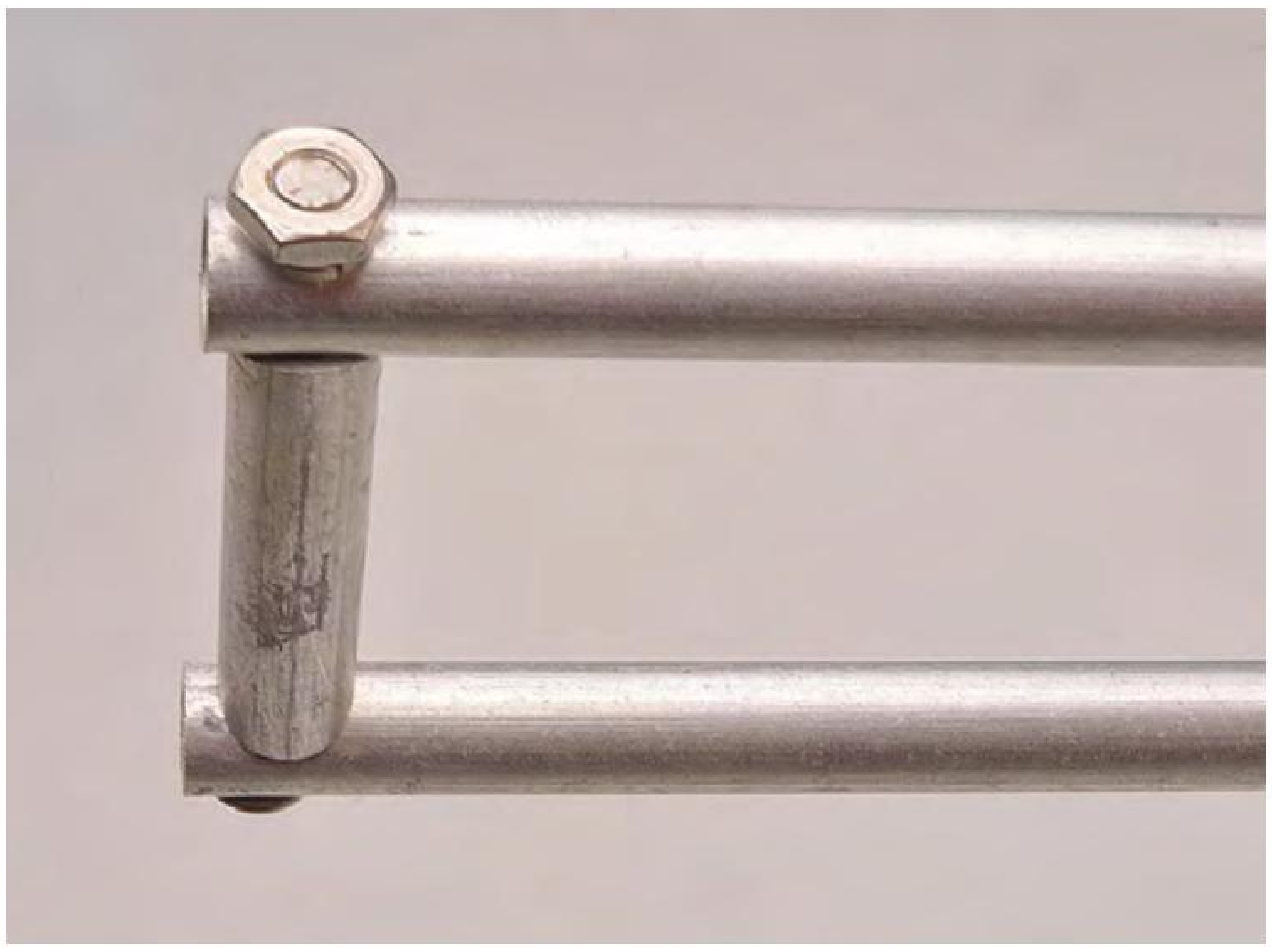
Before you start, make sure you have obtained all the aluminium and hardware listed in the bill of materials. You will be frustrated if you get half-way through and find you can't progress further because you lack screws or some other item. Get 'em all before you start!

Cut the boom to length first. It is 2222mm long and made of 19mm square aluminium tubing, which makes drilling and assembly easier. If you are experienced in metalwork and have access to a set of V-blocks and a drill press, you could substitute 25mm-diameter tubing for the boom. In fact, you could use 25mm stainless steel round tubing which is readily available from plumbing supply stores, but it is expensive and not easy to work.

While you're at it, cut the folded dipole spacer which also uses the 19mm square tubing. It is 50mm long. You should have a piece of tubing about 120mm-long left over as scrap. Don't throw it away. It will come in handy later. (When reassembling this prototype antenna after years in storage, we could not find the 50mm-long spacer so we



Note the two short sections of PVC conduit which act as spacers between the underside of the boom and the dipole insulator plate. Machine screws hold it all together. This is an alternative to the square tube spacer shown in Fig.1.



The ends of the folded dipole are fabricated using 42mm lengths of aluminium tubing shaped to mate with the upper and lower pieces. They are held together with 70mm-long machine screws, nuts and split washers.

substituted two 19mm lengths of 19mm plastic conduit instead).

Now cut the 10mm-diameter tubing for the director, three reflectors and parts for the dipole. Remember the old adage about 'measure twice and cut once'. It's hard to lengthen elements that are too short. Note that the three directors are all the same length, ie, 1270mm.

Next, centre-punch the boom for all holes prior to drilling. Note that the boom is 2222mm long and the total of the element spacings along the boom is 2182mm – see the plan diagram on Fig.1. Mark the hole centre position for the reflector element first, 20mm from one end of the boom, and then work your way along.

If you have a drill press which lets you drill all the element holes square through the boom you are fortunate. If not, mark the hole centre positions on both sides of the boom and drill from both sides. If you don't get the element holes lined up properly, you will have the elements skew-whiff.

A few words of advice on drilling is appropriate here. Drilling in thin-wall aluminium tubing can be a problem and many people tend to end up with holes that are more triangular than round. The way around this problem is to drill all the large holes (ie, all 10mm holes) under size and then ream them out to the correct diameter using a tapered reamer.

Be careful when reaming holes out though because it is quite easy to get carried away and then end up with holes that are too big. Use a scrap piece of 10mm tubing to test when the holes specified at 10mm are the correct size.

Each director element and the reflector is held in the boom with a self-tapping screw, as shown in diagram A of Fig.1. Drill a 3mm hole at the centre point of each element – but only through one side. Don't mount the elements on the boom yet though because the dipole should be assembled and mounted on the boom first.

Making the dipole

The folded dipole is made from five pieces of 10mm aluminium tubing, three long and two short. The detail of its assembly can be seen from the diagram at the bottom of Fig.1. The two short tubes, shown as diagram E on Fig.1, are cut and shaped using a file so that they key in with the top and bottom elements of the dipole. Further detail is shown in the accompanying photos.

The top and bottom pieces of the dipole are held at each end with a 70mm long 3/16-inch Whitworth or M4 screw, together with a nut and lock washer. At the centre, the lower halves of the dipole are terminated on an insulating plate (shown in diagram D of Fig.1). This plate is made of 3mm acrylic (Perspex or Lexan). The dipole halves are each secured to the insulating plate with a 19mm-long 3/16-inch Whitworth or M4 screw, nut and lock-washer.

What is a Yagi antenna?

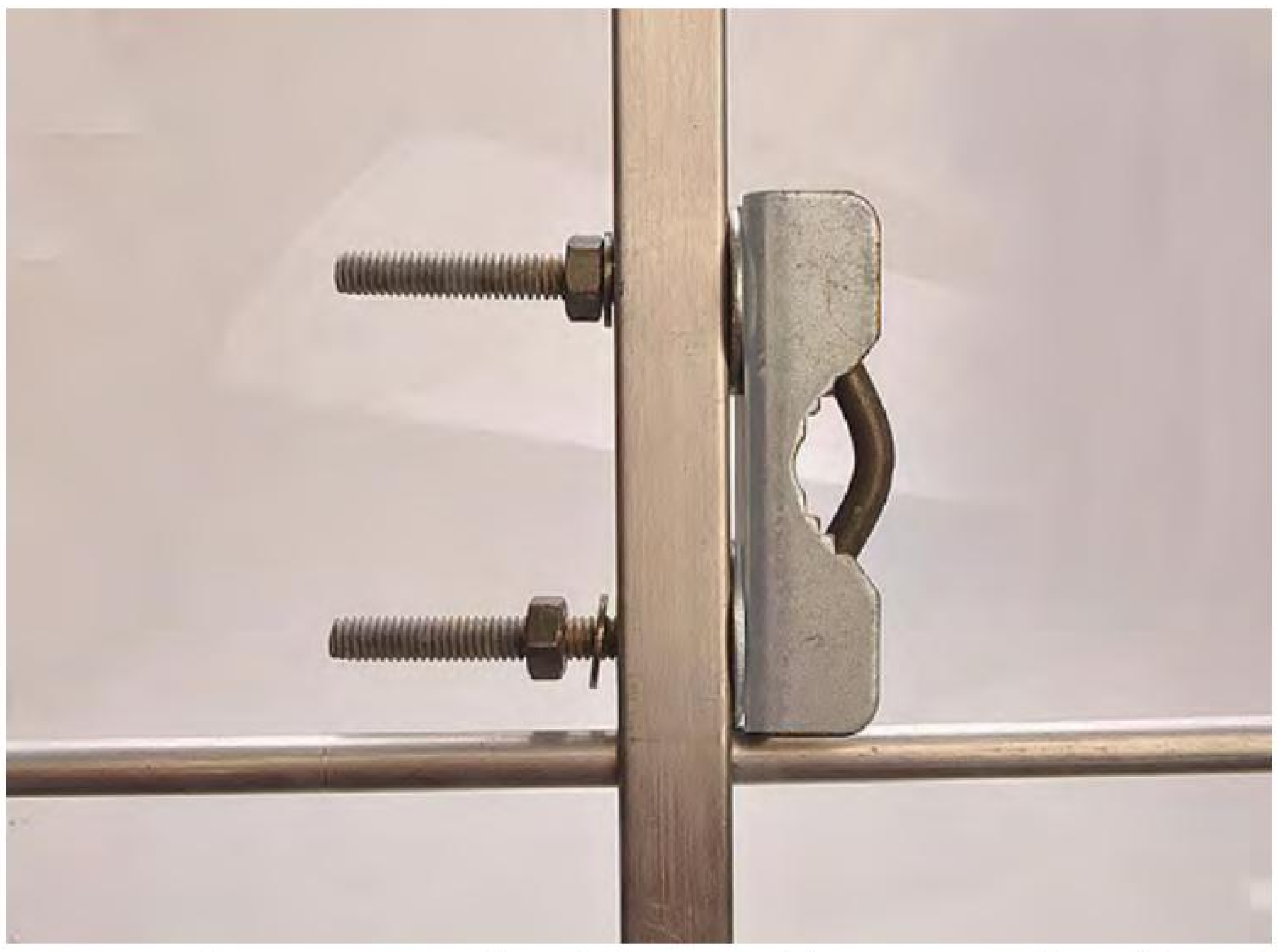
The Yagi antenna design was developed by H Yagi and S Uda at Tohoku Imperial University in Japan in 1926. In the VHF (very high frequency) bands, of which the FM band (88-108MHz) forms a small part, most antennas depend on electrically resonant elements, ie, elements which are a half-wavelength at the frequency of interest.

In its simplest form, the Yagi consists of a dipole element and an additional slightly longer parasitic element behind it, called the reflector. More complex designs have shorter parasitic elements in front of the dipole and these are called directors.

The reflector and directors are referred to as parasitic elements because they also resonate over a frequency range similar to that of the dipole. Part of the electromagnetic energy they capture is re-radiated and picked up by the dipole. Hence the director and reflectors add considerably to the signal which is picked up by the dipole on its own.

By suitably dimensioning the reflector and directors, it is possible to determine the overall frequency coverage of a Yagi antenna, its gain and its directional characteristics. In general, the more elements in a Yagi array, the higher will be its gain and the smaller the forward acceptance angle.

There is a law of diminishing returns though. Above a certain number of parasitic elements, no useful increase in gain is obtainable. There is a definite trade-off between the practical size of a Yagi and the amount of gain it provides.



We strongly recommend stainless steel (or at worst hot-dipped galvanised) fittings, as seen in this close-up shot of the U-bolt and V-block. You can find stainless fittings at automotive suppliers and ships' chandlers.

Do you have trouble drilling round holes? You'll do better by drilling the holes slightly undersize and then reaming them out to the exact size with a tapered reamer. Don't have a tapered reamer? Buy one – they're handy!

Terminals for the dipole are provided with two 32mm-long 3/16-inch Whitworth or M4 screws, each fitted with a nut and lock-washer plus a wing nut and flat washer.

The insulating plate is secured to and spaced off the main boom via a section of square tubing, shown as a 'folded dipole spacer' in diagram F of Fig.1. The insulating plate is secured to the spacer with two 32mm-long 8-gauge self-tapping screws which go through the spacer and into the boom. The top piece of the dipole is then secured to the boom with a 70mm-long 3/16-inch Whitworth or M4 screw, nut and lock-washer

The details of the dipole insulating plate and fixing to the boom can be seen in the accompanying photographs. Note that while we used white Perspex, you could use a piece of polycarbonate if that is what you have on hand. However, note our remarks on painting, later in this article.

By this time the antenna looks just about complete. You need to add the antenna clamp, to enable it to be attached to the mast and you will need a 300Ω-to-75Ω balun to match it to 75Ω coax cable.

You *could* use 300Ω ribbon if you wish (and also if you can get it!) and omit the balun, but to obtain the most interference-free signal, we recommend coax cable for your installation. Also, 300Ω ribbon deteriorates in the weather a lot faster than coax.

Unfortunately, many antenna clamps are sold with a cadmium-plated and passivated finish. These have a 'gold' finish. This is barely adequate for inland areas, but rusts quickly in sea air.

I may seem to be paranoid about corrosion but since my office is only a kilometre or so from the seaside I'm very aware of just how quickly metal hardware can rust and corrode.

If you can, buy U-bolts and clamps that are hot-dip galvanised or stainless steel, as used for car exhaust systems (or boat fittings), as these will last a lot longer. Be aware that zinc 'plated' fittings are not as rust resistant as galvanised types. Zinc-plated fittings have a smooth bright appearance while hot-dip galvanising is unmistakable – it has quite a rough appearance.

Whistling in the wind!

I also suggest that the ends of all the elements and the boom be stopped up with silicone sealant. This will stop them from whistling in the wind. Better still, you can buy Delrin plugs to suit the square aluminium tubing. These look neater.

It is also a good idea to paint your antenna, if you live in an area where corrosion is a problem. If nothing else, the dipole insulating plate should be painted as acrylic material does deteriorate in sunlight (ie, UV).

I suggest you leave the antenna for a month or so to weather it and then paint it with an etch primer. Finish it with an aluminium-loaded paint.

Installation

When you have finished your antenna you need to carefully consider its installation. There is no point in going to a lot of trouble making it if you don't install it properly.

Install your new antenna well away from TV antennas as these can have quite a serious effect on performance.

Similarly, solar panels (photovoltaic or hot water), metal wall siding, nearby metal guttering, electric cabling, metal roofing or sarking (ie, reflective insulation such as Sisalation) can all have a bad effect on antenna performance.

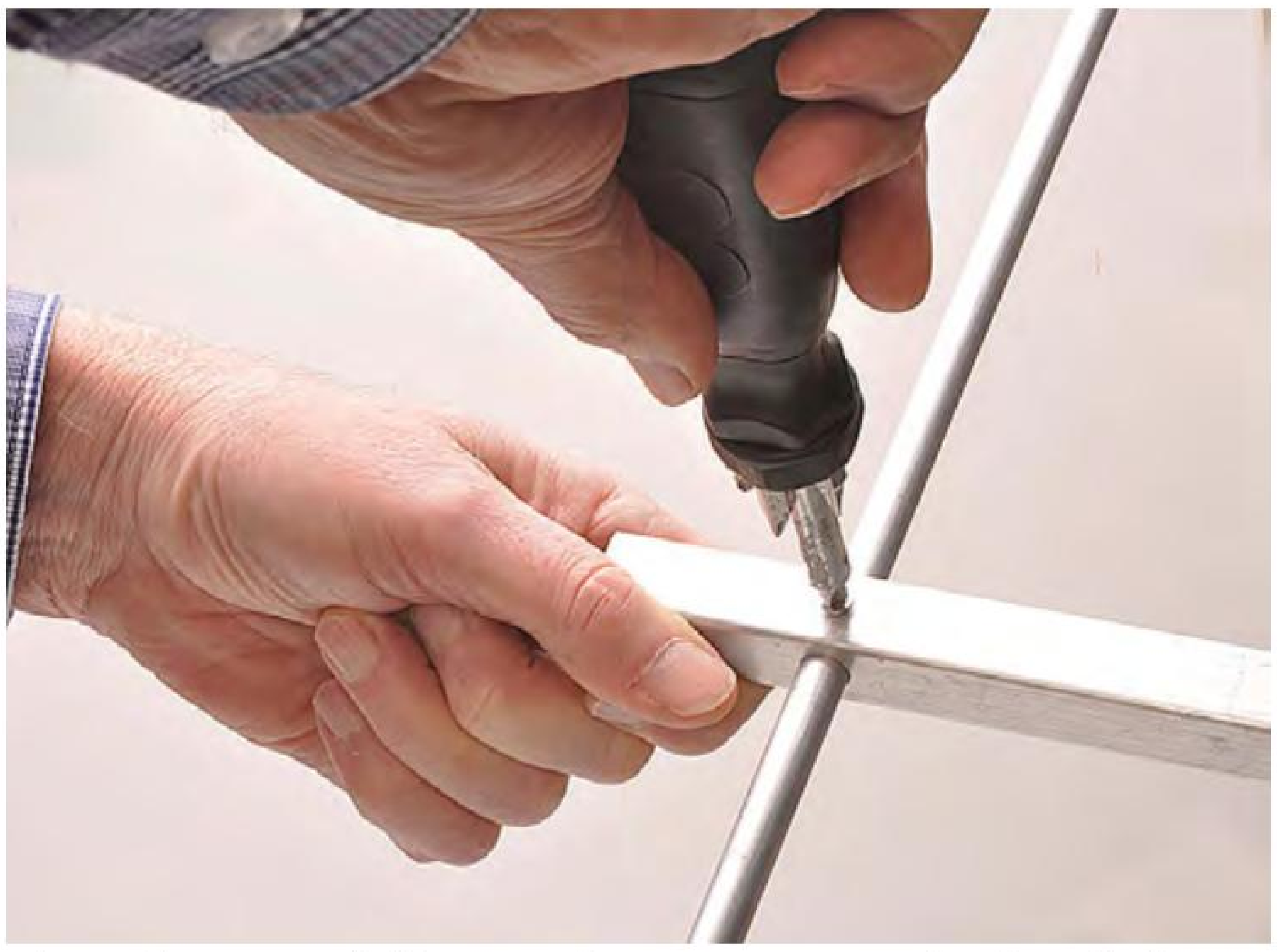
And don't forget the effect of a hot water tank which may be lurking just beneath the roof tiles.

If you live on a busy street, try to install your antenna as far away as possible from the traffic side of your house. That will help minimise ignition noise from passing traffic.

Finally, install the antenna as high as possible above the roof and guttering. If that is a problem, try to install the antenna so that it is at least a half wavelength away from the nearest metallic object such as guttering or roofing. This means a distance of about 1.5 metres away from guttering.

Take care during installation. Safe working with ladders is particularly important. Take your time and don't take risks – you don't want to end up listening to hospital radio!

Line up the antenna so that it its directors (the shorter elements) are aimed at the main FM station(s) of interest. You may have to call the station to check where their transmitter is located because they are seldom at the same location as the studios.



The reflector and director elements are attached to the boom using self-tapping screws. Ideally, all screws, nuts and washers should be stainless steel to avoid corrosion.

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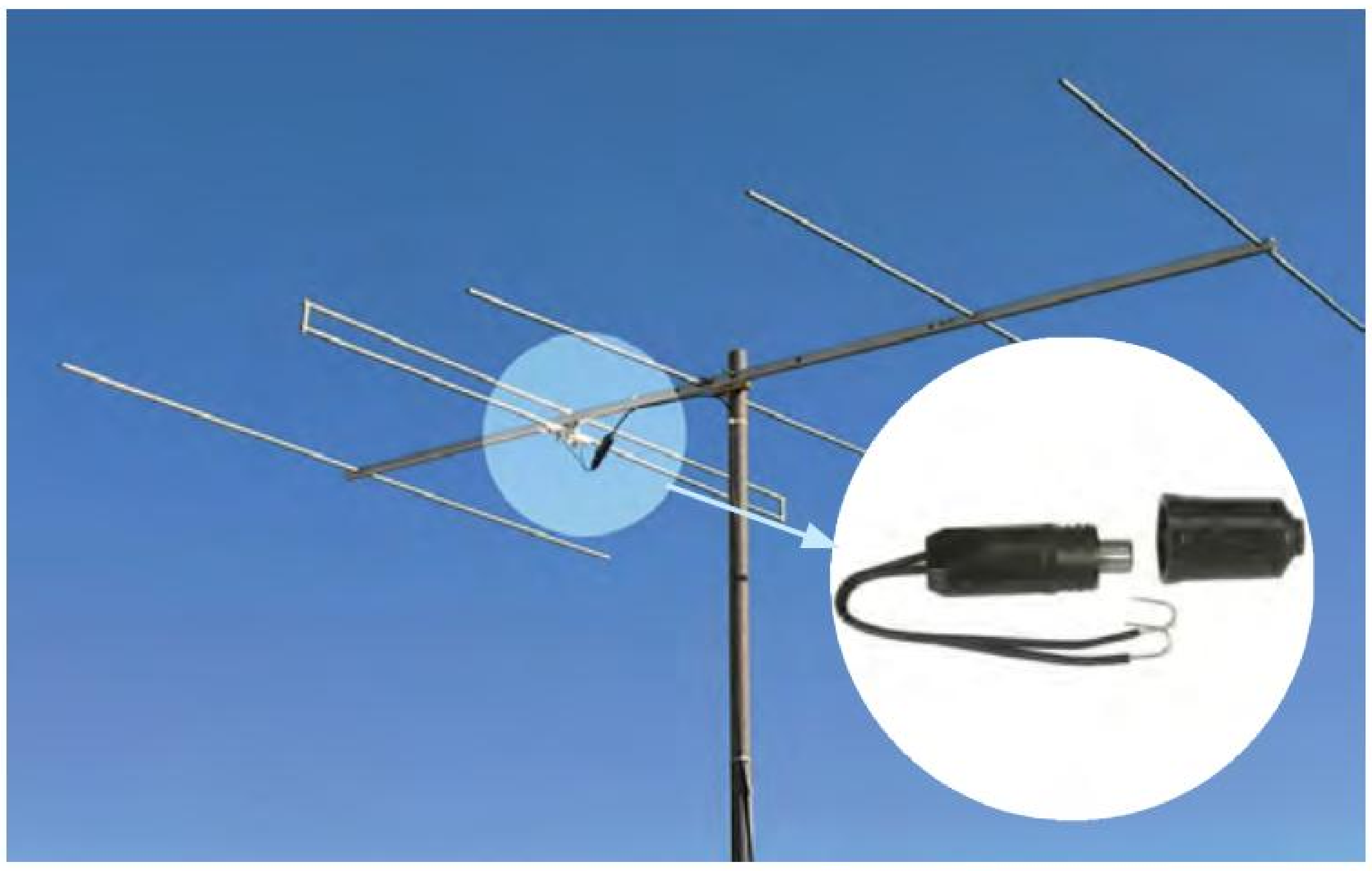
A tube-cutting tool makes easy work of cutting the aluminium rods to length, with nice square cuts. They're also handy if you have to cut PVC conduit. And they're cheap, too – from around £10.

Unfortunately, transmitters are often widely separated around cities, so you might have to compromise – aim at the one you most want or between them if there are two or more. But if you are really keen, you could consider installing a rotator, to obtain the very best reception from all stations.

You should find the stations come in loud and clear without too much fiddling around. If all you get is silence, or bad reception, check that your coax cable is connected properly and/or that it doesn't have a short somewhere (usually at the beginning or end).

Remember that coax cable is lossy so you want as short a length as you can install. And speaking of the coax, it should be firmly fixed to both the antenna boom and the mast. Otherwise it will flap around in the wind – annoying to start with but eventually leading to coax failure.

Use either black cable ties (don't use white – they don't last) or black self-annealing insulation tape.



Because the impedance of the folded dipole antenna is 300Ω and the coax cable downlead is 75Ω, an inline balun (balanced-to-unbalanced transformer) must be used to connect the coax cable to the driven element. It is essential that this be made waterproof with either a matching boot (normally supplied with balun) or, failing that, some coaxial sealing tape. Note also how the coax is firmly attached to both the antenna boom and to the mast pipe to stop it flapping in the breeze.

Bill of Materials
5-Element FM Antenna

Aluminium

2.3 metres of 19mm square aluminium tubing with 1.8mm wall thickness
8.5 metres of 10mm-diameter aluminium tubing with 1mm wall thickness

Hardware

1 piece of white Perspex or Lexan 120 x 40 x 3mm
1 galvanised or preferably stainless steel U-bolt and clamp to suit mast
4 8G × 13mm screws
2 8G × 32mm screws
3 3/16-inch Whitworth or M4 roundhead screws 70mm long
2 3/16-inch Whitworth or M4 roundhead screws 32mm long
2 3/16-inch Whitworth or M4 roundhead screws 19mm long
7 3/16-inch or 4mm ID split or lockwashers
7 3/16-inch Whitworth or M4 nuts
2 3/16-inch Whitworth or M4 wing nuts
2 3/16-inch or 4mm ID flat washers
Note: all screws, washers and nuts should be AS316-grade stainless steel

Miscellaneous

Mast and wall mounts or barge-board mount (hockey stick style)
300Ω-to-75Ω in-line balun (Jaycar Cat LT-3028 plus matching boot and F-connector)
Appropriate length semi-air-spaced coax cable (Jaycar WB-2004, WB-2006; Hills SSC32 or equivalent)
Plastic cable ties
Silicone sealant

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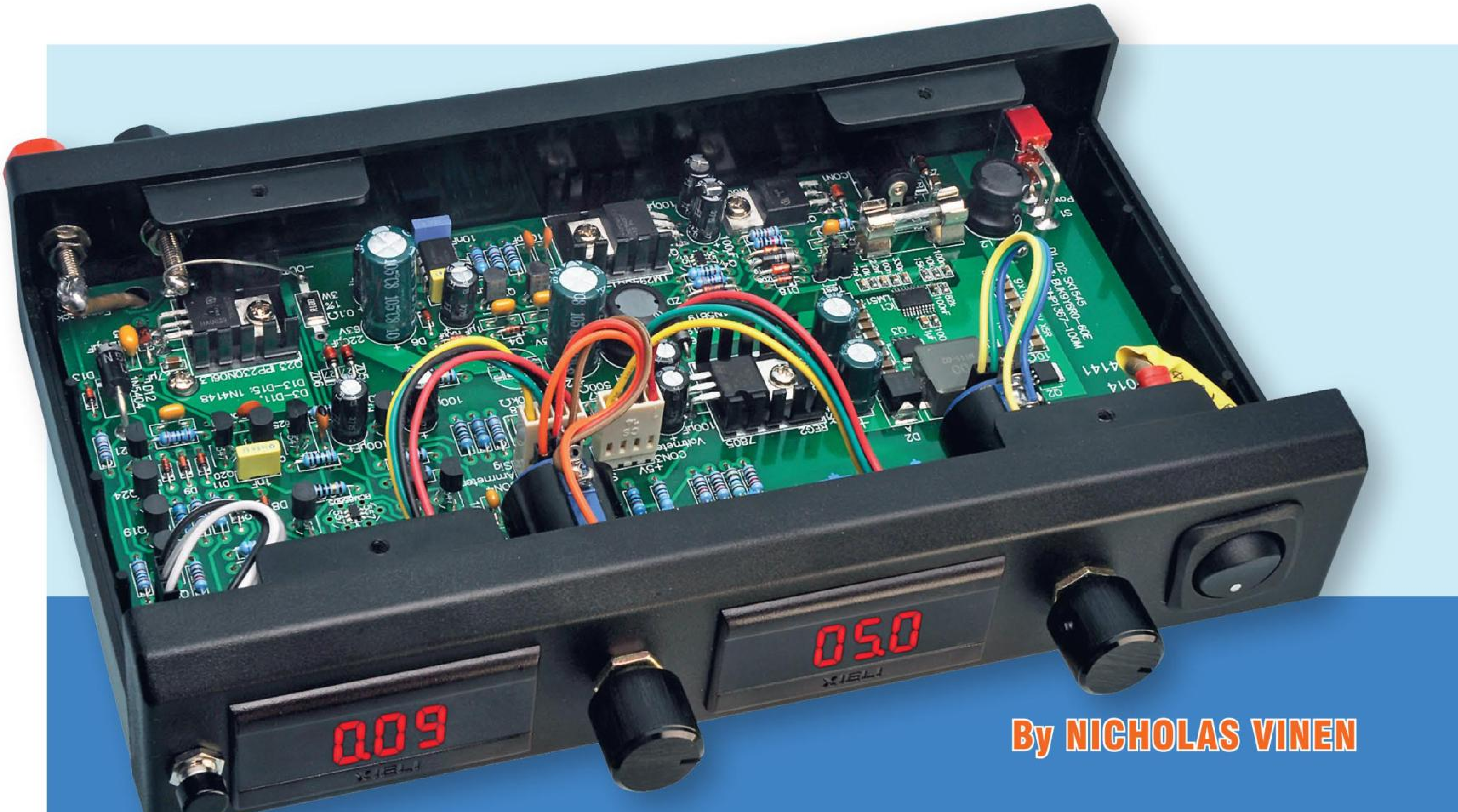


By NICHOLAS VINEN

100W Hybrid Switchmode / Linear Bench Supply – Part 2

Last month, we introduced our new 40V switchmode bench supply which can deliver up to 5A and fits into a compact rack-mount case with dual metering. This month, we describe the operation of the linear regulator circuit, discuss the PCB layout design and start the assembly by installing the parts on the PCB.

SINCE WE didn't finish describing the circuit last month, here's a quick refresher. The low-dropout (LDO) linear regulator determines the final output voltage and current, with the preceding switchmode section 'tracking' its output so that the input to the LDO is slightly higher than its output (by about 0.75V).

This gives the linear regulator sufficient 'headroom' to operate while keeping dissipation low – at 5A, the dissipation is around 5A × 0.75V = 3.75W, which is manageable with a small heatsink. This arrangement also means that if the current limit is set to a high level and the output is shorted, the switchmode regulator's output quickly drops to a low level and so the overall dissipation is kept reasonable.

A couple of different approaches can be taken when designing a low-dropout linear regulator. One is to use a PNP transistor or P-channel MOSFET as the pass element, and thus its base or gate is pulled towards ground to turn it on. The minimum drop-out voltage is simply the pass transistor's saturation voltage at full load current.

However, the fact that the base/gate voltage has to be pulled lower to increase the output current and higher to reduce it complicates the feedback system, since this type of arrangement can't have any 'local feedback'. This is why monolithic LDO regulators often have quite specific requirements for the output capacitor value and ESR to ensure stable operation; they rely solely on global feedback and the phase shift from the output capacitor forms a critical parameter for correct operation.

The other option is to use an NPN transistor or N-channel MOSFET with

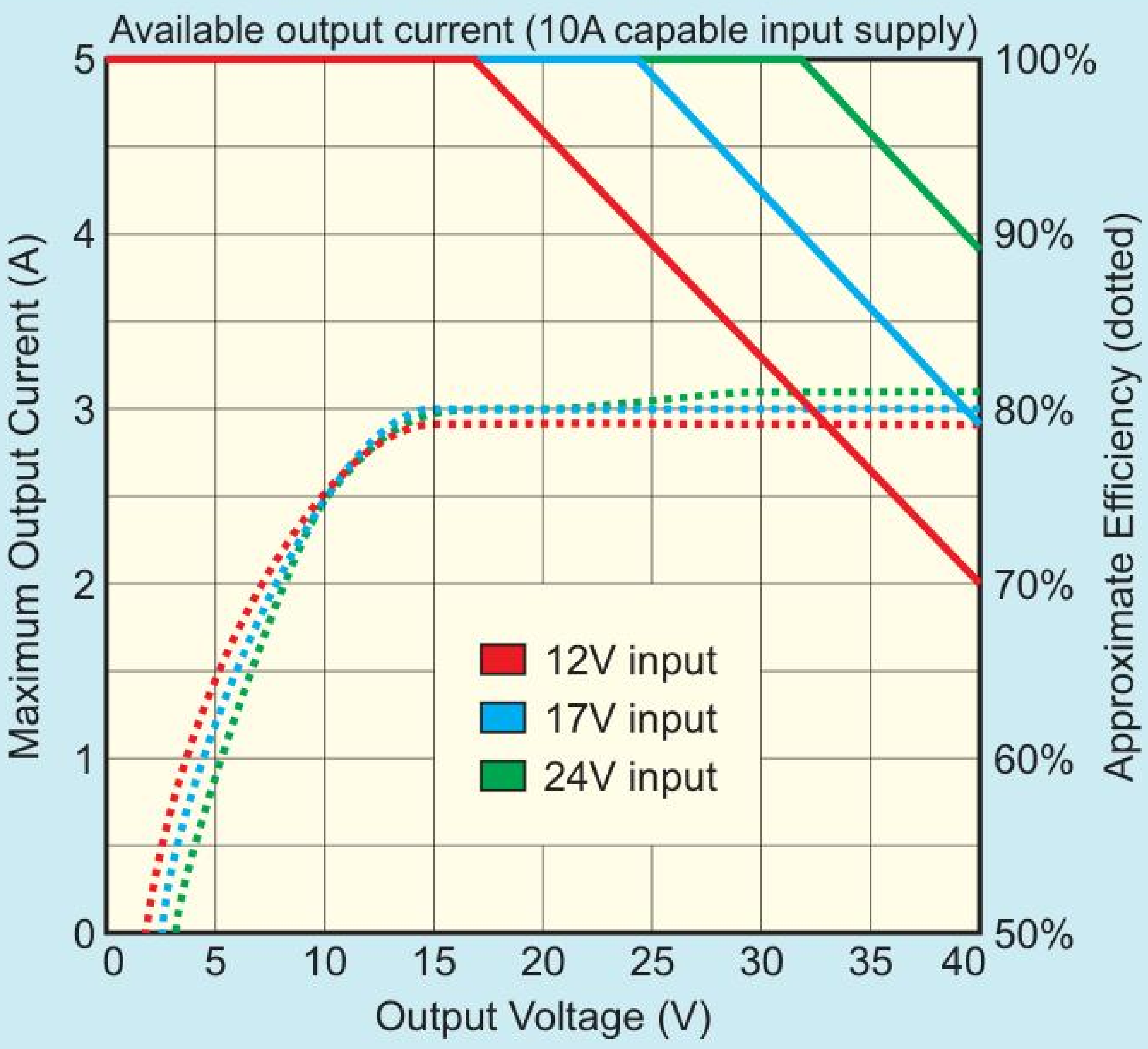
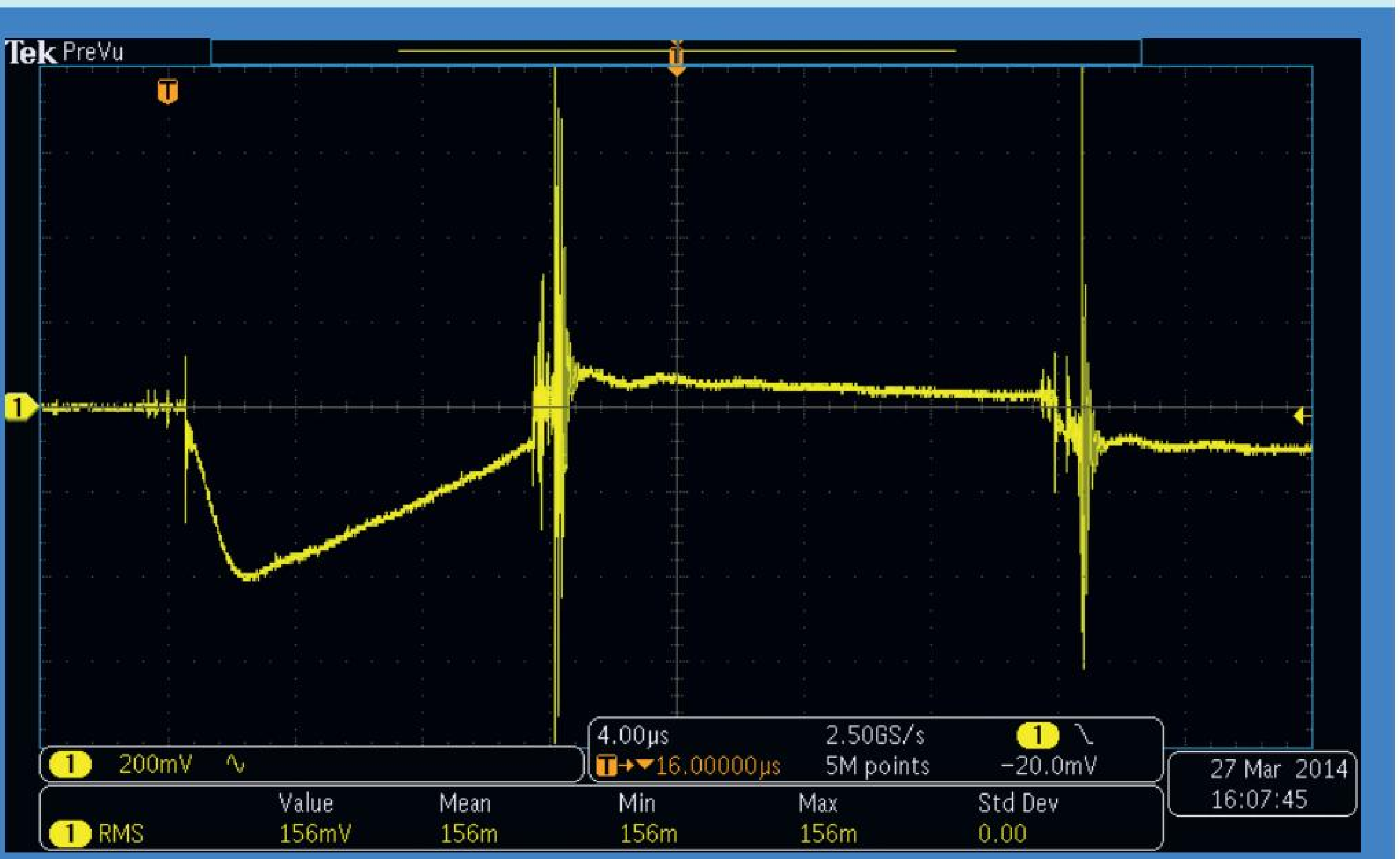


Fig.4: the circuit is capable of delivering 5A but this is limited at higher voltages by the power delivery capabilities of the DC supply and the 10A input limit. This graph shows how much current is available over the full output range for three common supply voltages. Note that the efficiency is best at lower output voltages. Note also that while the unit is capable of the indicated current, the switchmode section will get warm if operated at these limits for extended periods.



1 200mV ∿

4.00μs 2.50GS/s 1 ╲

T→▾16.00000μs 5M points −20.0mV

27 Mar 2014
16:07:45

	Value	Mean	Min	Max	Std Dev
1 RMS	156mV	156m	156m	156m	0.00

Fig.5: the output response with a 12V input, a 15V output and with a 1A load being rapidly connected and disconnected with no external output capacitor. The vertical scale is 200mV/div and the timebase is 4μs/div. As you can see, when the load current suddenly increases, the output drops but quickly recovers. There is a small amount of overshoot when the load is removed but it is well-controlled. The undershoot when the load is re-applied soon after is smaller than the first time as the switchmode section has not yet returned to idle operation.

its base/gate voltage driven from a 'boosted' supply rail somewhat above the main supply rail. In this circuit, we're using a MOSFET with a boosted supply that's around 10V above the output voltage. This allows us to vary the MOSFET's on-resistance from a very high value of many megohms when the output voltage is low and the load is light, to a very low resistance of around 15mΩ when it's delivering full-load current.

This arrangement gives superior regulation and filtering since it will inherently self-regulate to a certain extent. If the MOSFET's gate voltage is held constant, its source voltage (ie, the output) will be a certain amount lower than this and it will only vary over a small range (~1V), regardless of the drain voltage (ie, upstream supply).

Consider what happens if the output voltage (source terminal) drops and the gate voltage is constant. In this case, the MOSFET's gate-source potential increases and that turns the MOSFET on harder so that it conducts more current and thus pulls the output voltage up. Conversely, if the output voltage increases, the gate-source voltage drops and so the MOSFET conducts less current, thus reducing the output voltage.

While this mechanism is 'local' and therefore very fast, it isn't very accurate, as the gate-source voltage varies somewhat with temperature and channel current. So there still needs to be a global negative feedback mechanism to give an accurately regulated DC output voltage. However, this feedback system is less critical to performance thanks to that inherent local feedback.

Also, because there is less phase shift in this arrangement, the feedback loop doesn't have to be as heavily compensated and this allows the global feedback to act more rapidly, responding more quickly to sudden changes in load impedance.

Design details

There are a few regulator ICs which operate in this manner, but all the ones we could find have a fixed current-limit threshold, set by a low-value resistor in the main current path. That makes it awkward to implement a wide-range adjustable current limit.

As a result, we built our own regulator circuit. This is obviously more complex than using an IC, but the parts are cheap and commonly available, whereas ultra-LDO regulator controller ICs are somewhat expensive and hard to get.

Fig.6 shows the circuit of this linear regulator section. The labels at the edges match up to the labels on Fig.3, published in Part 1 last month, to show the connections between the two circuit sections. Taken together, these form the complete circuit of the bench supply.

The incoming supply rail (VIN) comes from the output of the switchmode regulator and its ripple filter, described last month. MOSFET Q23 controls current flow from this supply to the output (VOUT+), as described above, with its gate voltage typically 2V above the output voltage.

The regulator circuit is somewhat similar to that of an audio amplifier due to the need for accurate and fast-acting negative feedback. If you compare the two, you will find that there are broad similarities but subtle differences. The most obvious difference is that there are two differential input pairs, one to control the output voltage and the other to enforce the current limit. These are based around PNP transistor pairs Q14/Q15 and Q9/Q10 respectively.

Features and Specifications

Size and weight: 209 × 43 × 162mm, 400g
Input supply: 12-24V at up to 10A
Input under-voltage lockout: 11.3V
Output range: 0-40V at up to 5A (see Fig.4)
Output power: 100W+, depending on input supply voltage and current
Output ripple and noise: typically <5mV RMS @ 1A, ~1mV RMS at light load
Output capacitance: 2.2μF internal, handles any external capacitive load
Load regulation: <10mV for a 1A load step (measured at PCB terminals)
Line regulation: <5mV, 12-24V
Transient response: <500mV undershoot/overshoot for a 1A load step, recovery in ~10μs (no external capacitor) (see Fig.5)
Current limit response time: <150μs (short circuit @ 40V); <2ms to resume voltage regulation (depending on current limit)
Efficiency: ~70-80% (see Fig.4)
Voltmeter: resolution 0.1V, accuracy ±0.1V
Ammeter: resolution 10mA, accuracy ±10mA
Protection: fuse, cycle-by-cycle input current limiting, output current and voltage limiting
Current limit: continuously adjustable 0-5A, typically stable within ±1mA
Other features: view current limit, load switch

For accurate DC control, we need the base-emitter voltages of these transistor pairs to be fairly accurately matched (or rather, for the difference between them to remain constant) but this depends on temperature. So differential heating or cooling of these transistors due to air currents and so on, even of a fraction of a degree, can affect operation. As such, these transistor pairs are thermally bonded so that they remain at the same temperature.

This can be achieved in one of two ways: either by using two transistors in a single package or by bonding two separate transistors with thermally conductive paste. The PCB is designed for either approach, but thermal tracking is better when the two transistors are in a single package, so we have used the BCM856DS dual-matched transistors for our prototypes. We suggest you do the same.

These are rather neat devices, being equivalent to two BC556s in a 6-pin surface-mount package. The current gain (h_{FE}/beta) and base-emitter voltages are matched to within 10% and 2mV respectively. They are quite affordable and available in three different packages; we are using the largest one since it is easier to solder.

To understand the operation of the regulator as a whole, start by considering voltage-monitoring transistor pair Q14 and Q15. The two emitters are fed with a constant current of about 1mA by PNP transistor Q13, with this current set by the 680Ω resistor at its emitter. A bias voltage fed to Q13's base via a 2.2kΩ resistor from Q18 acts to keep around 0.6V across the 680Ω resistor.

This differential pair has 47Ω 'emitter degeneration' resistors to reduce the overall gain somewhat and improve linearity, which aids stability. The collector currents are kept more or less equal by a current mirror consisting of NPN transistors Q16 and Q17. This keeps the circuit operating consistently despite large variations in supply voltage as the output voltage varies.

Q14's base is tied to the negative output terminal (ie, effectively ground) via a 22Ω resistor, while Q15's base goes to the output feedback divider (shown in Fig.3 last month) via 'OV-feedback'. This is a divided-down version of the output voltage, as set by VR1, the voltage adjustment pot.

When the regulator's output voltage increases, the voltage at Q15's base also increases, reducing the current through Q15. Since the collector currents are mirrored, this means that more of the 1mA total emitter current must flow from Q14 to D7 to maintain an equal current through Q16 and Q17.

D7 feeds the base of Q25, so as this current flow increases, its collector voltage drops, reducing the drive voltage to the NPN/PNP emitter-follower push-pull pair of Q21 and Q22. This in turn pulls down Q23's gate, reducing the output voltage until it is back

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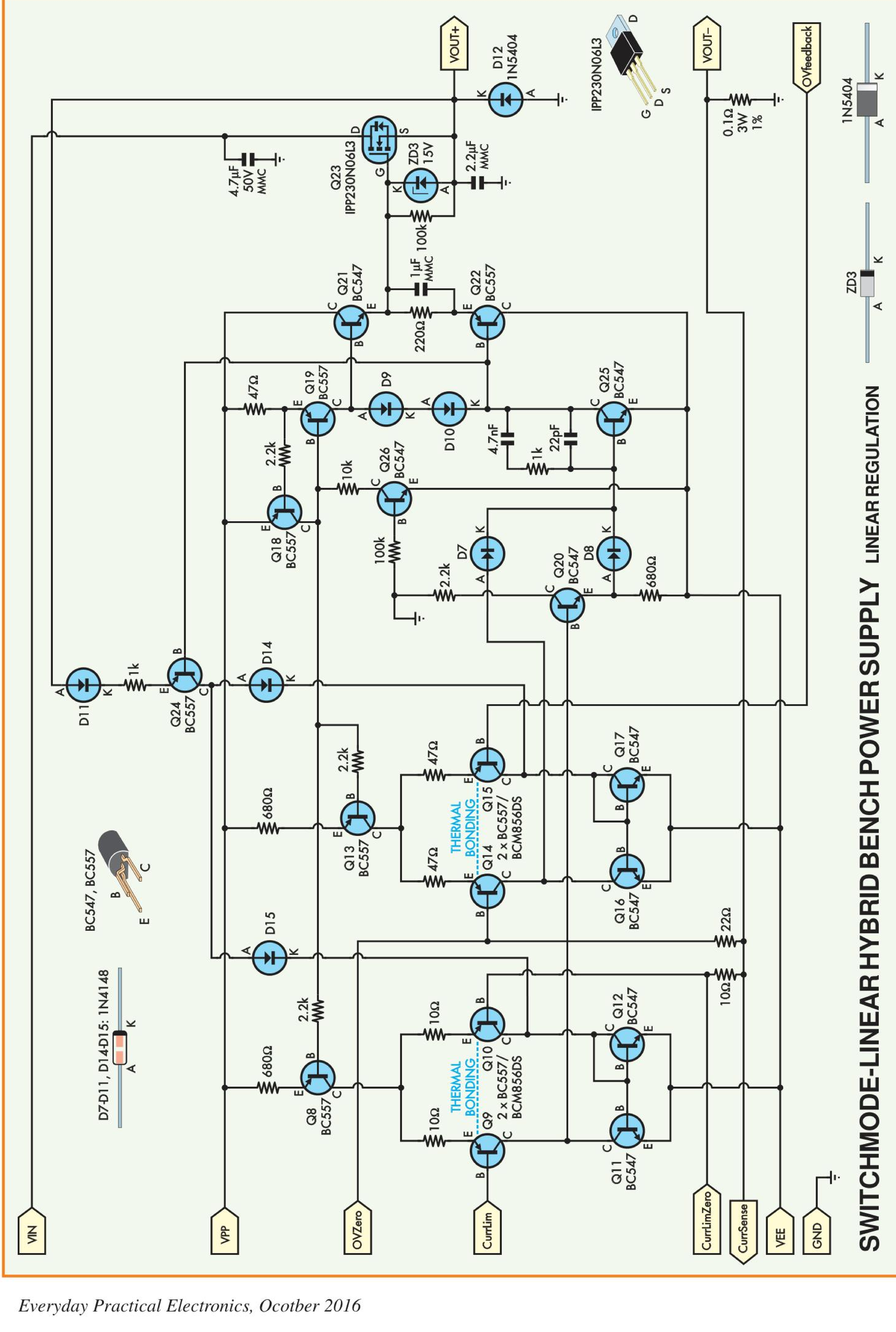

VIN
VPP
OVZero
CurrLim
CurrLimZero
CurrSense
VEE
GND
VOUT+
VOUT–
OVfeedback
D11
1k
Q24
BC557
D14
D15
Q8
BC557
680Ω
2.2k
Q13
BC557
Q18
BC557
Q19
BC557
47Ω
Q21
BC547
Q22
BC557
220Ω
1µF
MMC
100k
ZD3
15V
2.2µF
MMC
Q23
IPP230N06L3
4.7µF
50V
MMC
D12
1N5404
D9
D10
4.7nF
22pF
Q25
BC547
Q26
BC547
10k
D7
D8
Q20
BC547
680Ω
Q9
Q10
2 x BC557/
BCM856DS
THERMAL
BONDING
10Ω
Q14
Q15
Q11
BC547
Q12
BC547
Q16
BC547
Q17
BC547
22Ω
0.1Ω
3W
1%
BC547, BC557
E B C
D7-D11, D14-D15: 1N4148
A K
IPP230N06L3
G D S
ZD3
1N5404

SWITCHMODE-LINEAR HYBRID BENCH POWER SUPPLY LINEAR REGULATION

Fig.6: the linear section of the circuit diagram. This matches up with the switchmode section published last month (Fig.3) via the labelled inputs and outputs. This is essentially a self-contained ultra-low-dropout linear regulator with adjustable current limiting. Q14 and Q15 compare the feedback voltage to a ground reference and regulate the output voltage while Q9 and Q10 enforce the current limit by comparing it against the voltage across the 0.1Ω shunt. There is provision to zero (trim) the output voltage and current limit via OVZero and CurrLimZero respectively.

Parts List

1 double-sided PCB, available from the *EPE PCB Service*, coded 18104141, 198 × 95mm
1 half-rack plastic instrument case with two integrated LED panel meters and SPST rocker switch (available from Altronics)
2 M205 fuseholder clips
1 10A M205 fast-blow fuse (F1)
1 10µH 15.5A 5MHz shielded SMD inductor, 14 × 14mm (L1) (SCIHP1367-100M; Digi-Key Cat 595-1400-1-ND)
2 3.3µH 5.6A bobbin inductors (L2,L3) (RLB1314-3R3ML; element14 Cat 2333682, Digi-Key Cat RLB1314-3R3ML-ND)
1 PCB-mount DC socket (CON1)
1 pair red and black chassis-mount binding posts (CON2)
2 4-way polarised headers and matching header plugs with crimp pins (CON3, CON4)
2 3-way polarised headers and matching header plugs with crimp pins (CON5, CON6)
1 SPDT PCB-mount right-angle toggle switch (S1)
1 small chassis-mount SPDT momentary pushbutton switch (S2)
2 3-pin headers (LK1,S2)
1 2-pin header (LK2)
2 jumper shunts (LK1,LK2)
1 3-pin female header plug or cable with suitable plug (for S2)
2 10kΩ linear 10-turn panel-mount potentiometers (VR1 - VR2) (eg, Rockby 41645***, Element14 1144798/1612609/1386483 etc)
OR
2 10kΩ linear chassis-mount standard potentiometers
4 500Ω mini horizontal trimpots (VR3-VR6; VR7 optional)
1 20kΩ mini sealed horizontal trimpot (VR8, optional)
2 knobs to suit VR1 and VR2
1 ferrite bead (FB3)
3 6073B-type TO-220 ‘Micro-U’ heatsinks
4 M3 × 6mm machine screws/nuts
1 150mm-length rainbow cable or assorted light-duty hookup wires
1 100mm-length tinned copper wire
1 500mm-length extra-heavy duty hookup wire
2 6.8mm female spade crimp connectors to suit extra-heavy duty wire
4 No.4 × 6mm self-tapping screws
2 M3 × 5mm black machine screws
*** Limited stock available

Semiconductors

1 LM5118MH(X) buck/boost switchmode regulator IC (IC1) (Element14 Cat 1606457, Digi-Key Cat LM5118MHX/NOPBCT-ND)
1 7555 CMOS timer IC (IC2)
1 LM2940CT-12 12V 1A low-dropout regulator (REG1)
1 7805 +5V 1A regulator (REG2)
1 79L05 -5V 100mA regulator (REG3)
1 LM285Z-2.5 voltage reference (REG4)
1 IRF1405 or IPP230N06L3 N-channel MOSFET (Q1)
2 60V 100A N-channel SMD logic-level MOSFETs (Q2,Q3) (Digi-Key Cat. 568-10984-1-ND)
3 BCM856DS dual PNP SMD transistors (Element14 Cat 1829188, Digi-Key Cat 568-6834-1-ND) OR
6 BC557 100mA PNP transistors (Q4,Q5,Q9,Q10,Q14,Q15)
1 BC327 NPN transistor (Q6)
1 BC337 PNP transistor (Q7)
6 BC557 100mA PNP transistors (Q8,Q13,Q18,Q19,Q22,Q24)
8 BC547 100mA NPN transistors (Q11,Q12,Q16,Q17,Q20,Q21,Q25,Q26)
1 IPP230N06L3 N-channel MOSFET (Q23)
2 SK1545 45V 15A SMD Schottky diodes (D1,D2) (Digi-Key Cat. SK1545-TPCT-ND)
13 1N4148 signal diodes (D3-D11,D13-D15,D18)
3 1N5819 1A Schottky diodes (D16,D17,D19)
1 1N5404 3A diode (D12)
3 15V 1W Zener diodes (ZD1,ZD3,ZD8)
4 27V 1W Zener diodes (ZD2,ZD5-ZD7)
1 4.7V 0.4W or 1W Zener diode (ZD9)

Capacitors

2 220µF 50V/63V low-ESR electrolytics
8 100µF 25V electrolytics
2 47µF 50V/63V low-ESR electrolytics
9 10µF 25V X5R SMD ceramic, 3216 (imperial 1206) or 2012 (imperial 0805) package
10 4.7µF 50V X5R SMD ceramic, 3216 (imperial 1206) or 2012 (imperial 0805) package
1 2.2µF 50V MMC*
3 1µF 50V MMC*
1 1µF 50V X5R SMD ceramic**
2 100nF 50V ceramic disc or MMC*
4 100nF 50V X7R SMD ceramic**
1 10nF 50V MKT or MMC*
1 10nF 50V X7R SMD ceramic**
1 4.7nF 63V MKT
1 4.7nF 50V X7R SMD ceramic**
1 2.2nF 63V MKT
1 2.2nF 50V X7R SMD ceramic**
1 330pF 50V C0G/NP0 SMD ceramic**
3 100pF 50V ceramic disc
1 22pF 50V ceramic disc

Resistors (0.25W, 1% unless stated)

2 10MΩ
1 1MΩ
1 910kΩ
5 100kΩ
1 82kΩ 1% SMD**
1 15kΩ 1% SMD**
4 10kΩ
2 10kΩ 1% SMD**
1 9.1kΩ
2 3.3kΩ
7 2.2kΩ
1 1.8kΩ
2 1kΩ
2 820Ω
5 680Ω
2 470Ω
1 220Ω
3 47Ω
1 22Ω
5 10Ω
1 10Ω 1% SMD**
1 0.1Ω 1% 3W SMD 6432 (2512 imperial) (element14 Cat 1435952, Digi-Key Cat CRA2512-FZ-R100ELFCT-ND)
OR
1 0.1Ω 1% 3W through-hole resistor (Welwyn OAR-310F or similar)
1 15mΩ 0.75W or 1W SMD 3216 (1206 imperial) (element14 Cat. 1887165, Digi-Key Cat. MCS1632R015FERCT-ND)

* *Monolithic Multi-layer Ceramic*
** *These SMD passive components can be in either 1608 (imperial 0603) or 2012 (imperial 0805) packages*

where it should be and the bases of Q14 and Q15 are then at the same voltage.

Conversely, if the output voltage drops, the reverse occurs and the voltage at Q23's base increases to compensate.

Q25 has a 22pF Miller capacitor to reduce the AC open-loop gain at high frequencies, to keep the feedback loop stable, otherwise Q23's gate voltage would not settle down. In parallel with this Miller capacitor is a 4.7nF capacitor with a series 1kΩ resistor. This improves stability when a high-value capacitor is connected to the output of the supply, avoiding excessive voltage overshoot. It also helps stabilise the voltage during current limiting.

The 2.2µF output capacitor is also important for stability and this and the Miller capacitor component values have been chosen as a compromise between stability, fast transient response and a low output capacitance so that the supply can more closely approximate an ideal current source.

Q25's collector load is another constant current source, this time providing around 12.5mA. It's controlled by Q19 which (like Q8 and Q13) is biased by Q18, in turn biased by a 10kΩ resistor to the negative supply via Q26. The 47Ω resistor sets the current through Q19 to 0.6V / 47Ω = ~12.5mA. This value was chosen based on the 625mW dissipation limit for Q25, given the maximum possible voltage across it of around 46V, when the output is at 40V.

Diodes D9 and D10, in series with Q25's collector, bias the base-emitter junctions of buffer transistors Q21 and Q22 so that they are both slightly conducting all the time. This speeds up the 'hand-off' between them as the output switches from slewing positive to negative and vice versa.

The quiescent current through this pair is limited by a 220Ω resistor which is bypassed with a 1µF capacitor so that Q23's gate can be quickly discharged by Q22. Note that the relatively high 12.5mA through this stage is required so that Q23's gate can be quickly charged when the output is slewing in the positive direction, eg, when recovering from a brief short circuit.

Zener diode ZD3 clamps Q23's gate voltage to no more than 15V above its source. Normally, the supply rails guarantee this, but under some conditions it could be exceeded, hence the zener clamp.

PCB design and layout

The main part of the article describes how the circuit works, but that isn't the end of the story. Let's look at a couple of the trickier aspects of the PCB design.

The most obvious place where layout is critical is around the switchmode regulator, ie, IC1, D1, D2, Q2, Q3 and L1. We've purposefully chosen small components here, while also taking into account ease of soldering. The rationale behind this is that by keeping the components small, the distance through which high switching currents must flow is kept to a minimum and thus the resistance and parasitic inductance of the short, wide PCB tracks used is kept to a minimum. The current flowing through these components thus also stays close to the PCB's ground plane.

This ground plane acts as a shorted turn for the various parasitic inductors (transformers) formed by loops in the circuit, but this isn't perfect – it is on the other side of the PCB (~1.5mm away) and does not have zero resistance. So it's good practice to keep those loops as small as possible.

The layout of this switchmode section is based on the demonstration board for the LM5118 IC*. This is a rather clever scheme whereby the current runs around the edge, from the input at lower left up to the top, then across to the right and then down to lower-right. The central area is a large power groundplane to which the IC is connected and there are dozens of vias connecting this to the underside of the PCB where the groundplane covers nearly 100% of the area under the current-carrying components.

The idea behind this is that while current flows in a clockwise direction around this section, the return current flowing through ground goes in an anti-clockwise direction around the groundplane. This is because current follows the path of least impedance (not just resistance) and this is true when the parasitic inductance is minimised, ie, when the return current flows directly underneath the main current path.**

There is a separate analogue ground plane below pins 1-10 of the IC (ie on the underside), above which the analogue components are mounted (eg, compensation and feedback networks). The two groundplanes are joined under the IC. This keeps the switching noise out of the analogue components.

The LM5118 has a large pad on its underside which is soldered to the PCB to provide heatsinking for the IC. The large copper area it's connected to helps draw heat away, too. Since constructors won't necessarily have a hot air or reflow station to solder the IC, we have placed three large vias through this pad and onto the bottom side, so that solder can be flowed through to this pad from underneath.

Finally, a note on the layout of the analogue section. The ground return paths for the two panel meters have been brought back to the earth plane separately from other tracks so that the relatively high current flow (250-300mA) does not create ground voltage shifts to upset the meter readings or other circuitry. After all, the lowest digit on each meter has a resolution of just 0.1mV.

** See Texas Instruments application note AN-1819 at:* ***www.ti.com/lit/ug/snva334b/snva334b.pdf***

*** Some good information on current flows in double-sided PCBs can be found here:* ***www.analog.com/library/analogdialogue/archives/41-06/ground_bounce.html***

Q23's gate voltage is prevented from going below the output voltage by Q24. As the gate goes negative, Q24's base is pulled below its emitter and thus delivers current to the collectors of Q17 and Q12 via diodes D14 and D15. This forces the drive to Q25's base to be reduced, thus preventing Q23's gate from dropping any further. The zener will also do this job, however the advantage of including Q24 is that it also acts to clamp Q25's collector voltage, giving much faster recovery from current limiting.

Q26 ensures a clean start-up when power is first applied. It prevents the bias current for Q8, Q13 and Q19 from flowing to VEE via the 10kΩ resistor until the VEE negative rail has dropped below about −1V. Without this bias, Q19 remains off and so Q25's collector voltage remains low until the supplies stabilise. The 100kΩ resistor across ZD3 keeps Q23's gate discharged

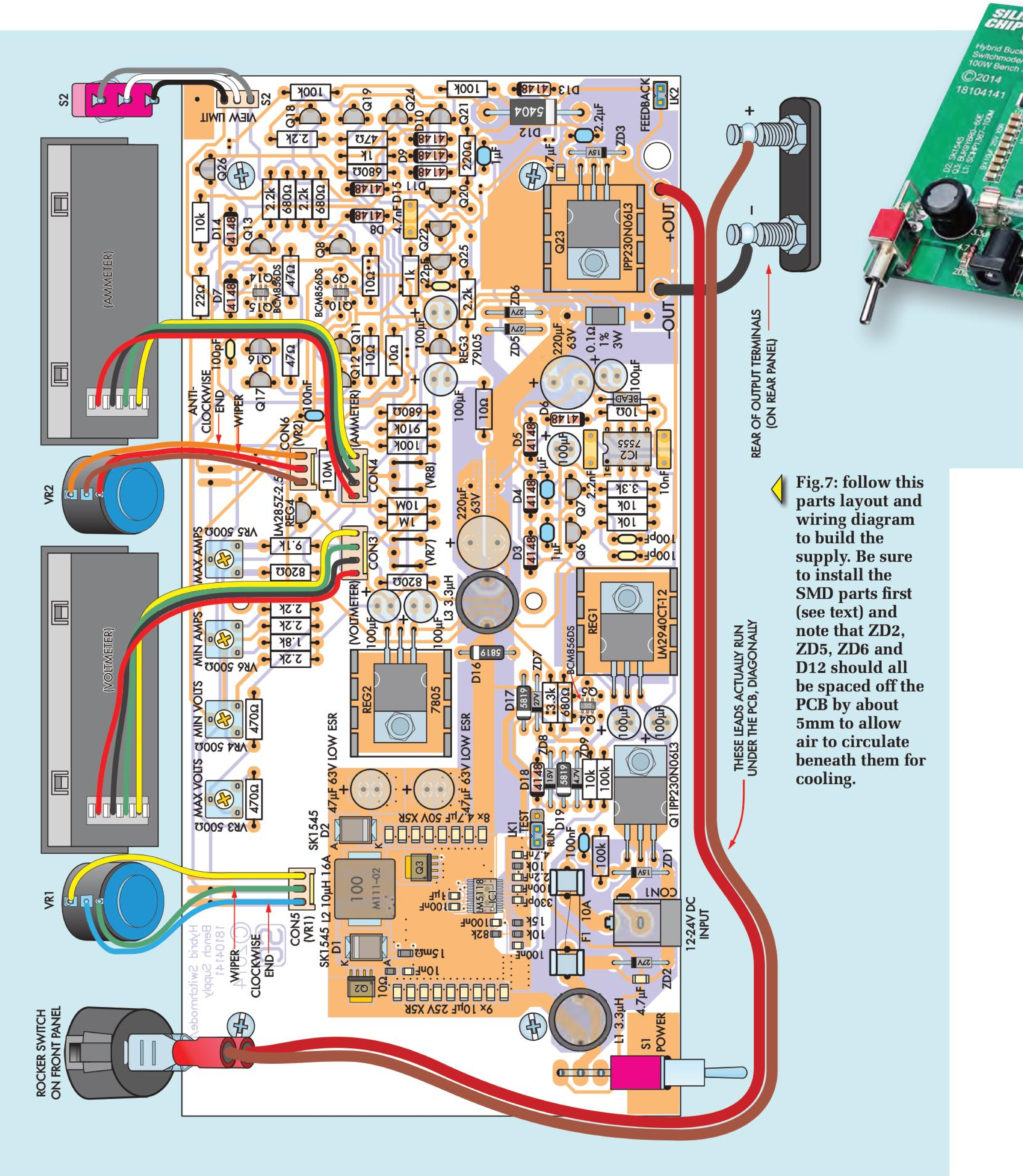
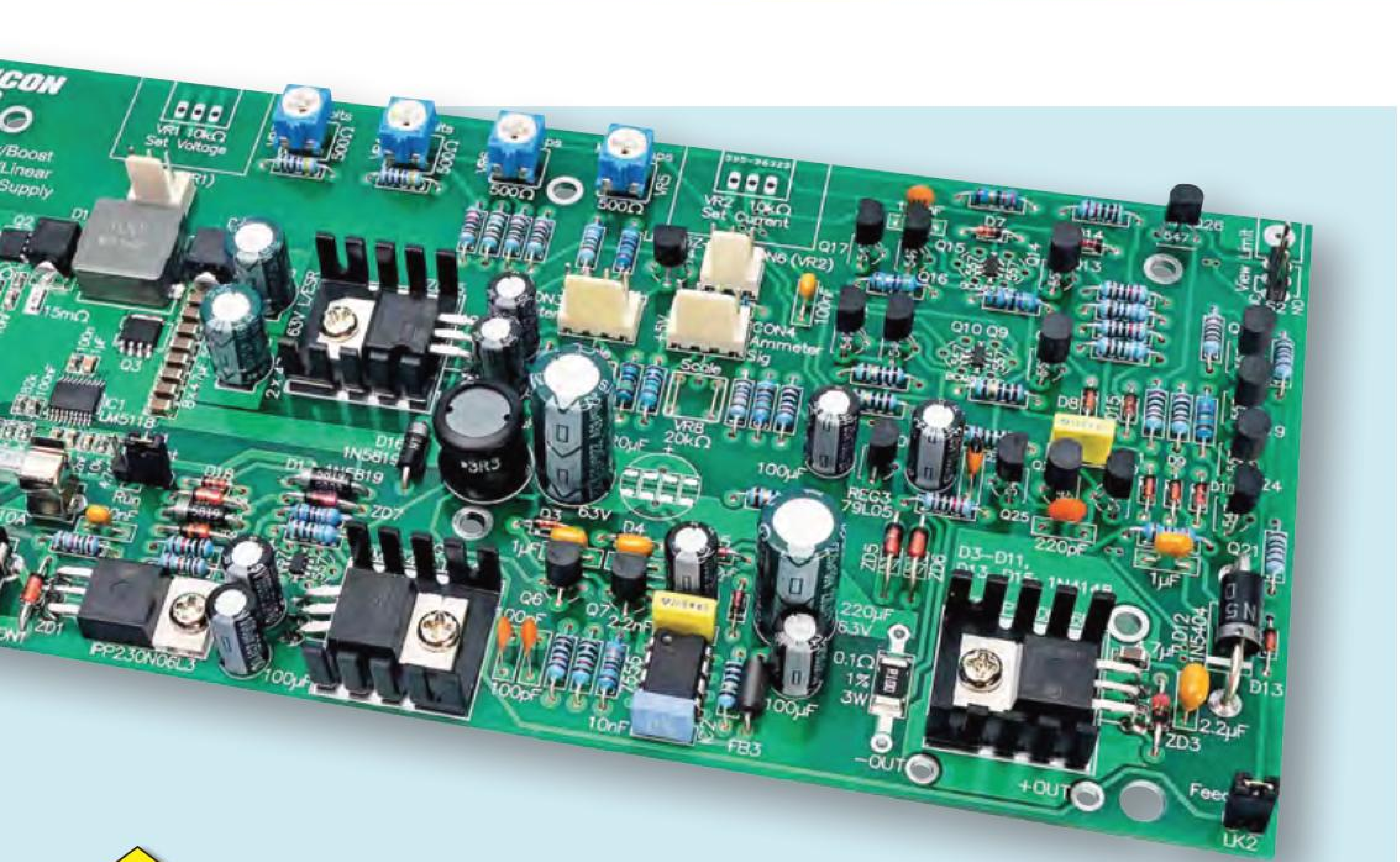

S2
VIEW LIMIT
(AMMETER)
(VOLTMETER)
VR2
VR1
ANTI-CLOCKWISE END
WIPER
CLOCKWISE END
CON6 (VR2)
CON4 (AMMETER)
CON3 (VOLTMETER)
CON5 (VR1)
MAX AMPS VR5 500Ω
MIN AMPS VR6 500Ω
MIN VOLTS VR4 500Ω
MAX VOLTS VR3 500Ω
REG1 LM2940CT-12
REG2 7805
REG3 79L05
REG4 LM285Z-2.5
Q23 IPP230N06L3
Q1 IPP230N06L3
IC2 7555
IC1 LM5118
L1 3.3µH
L2 10µH 16A
L3 3.3µH
D1 SK1545
D2 SK1545
D12 5404
8x 4.7µF 50V X5R
9x 10µF 25V X5R
47µF 63V LOW ESR
F1 10A
CON1 12-24V DC INPUT
S1 POWER
LK1 TEST RUN
LK2 FEEDBACK
+OUT
–OUT
0.1Ω 1% 3W
ROCKER SWITCH ON FRONT PANEL
REAR OF OUTPUT TERMINALS (ON REAR PANEL)
THESE LEADS ACTUALLY RUN UNDER THE PCB, DIAGONALLY
Hybrid Switchmode Bench Supply 18104141
SILICON CHIP
©2014
18104141

Fig.7: follow this parts layout and wiring diagram to build the supply. Be sure to install the SMD parts first (see text) and note that ZD2, ZD5, ZD6 and D12 should all be spaced off the PCB by about 5mm to allow air to circulate beneath them for cooling.

during this time, so it remains off and the output voltage stays low.

Note that we want to be sure that when OVFeedback is connected to VOUT+ via a low resistance (ie, voltage adjustment pot VR1 is at minimum), the output voltage is zero. This depends on how accurately Q14 and Q15 are matched and also on VR1's tolerances.

These error sources are trimmed out by injecting a small current from 'OVZero' into the base of Q14 (from trimpot VR4, in Fig.3 last month). This develops a maximum of a few



This view shows the completed PCB, ready for installation in the case. Follow the procedure described in the text to solder in the SMD parts.

millivolts across the 22Ω resistor and allows the output to be nudged one way or the other.

Current limiting and regulation

The current-regulation mechanism operates similarly to the voltage feedback described above. Differential input pair Q9 and Q10 is configured identically to Q14 and Q15, except that 10Ω emitter-degeneration resistors are used rather than the 47Ω. That's because the voltage levels applied to this differential pair are much lower (500mV max).

Also, rather than the output current from this differential front-end driving Q25 directly, it's amplified by Q20. This is required because if the output current exceeds the set level by 1mA (for example), the voltage difference between the bases of Q9 and Q10 is just 0.1mV. However, we want the output voltage to drop rapidly as soon as the current limit is exceeded by even a small amount, and so Q20 provides additional current gain of around 250.

Q9's base is the non-inverting input of the pair and this is connected to VR2's wiper. This is the current limit adjustment potentiometer ('CurrLim') and it supplies a 0-500mV signal to set the current limit to between 0 and 5A. Q10's base is connected to the top of the 0.1Ω current-sense resistor via an additional 10Ω resistor. This allows a small current injection from the 'CurrLimZero' input to pull this a few millivolts one way or the other, to cancel out the differences in the base-emitter voltages of Q9 and Q10.

Thus, if the voltage across the sense resistor exceeds the voltage from VR2's wiper, current flow from Q9 to Q20's base increases and thus D8 becomes forward-biased. This pulls Q25's collector down and thus reduces the output voltage until the current flow stabilises at the set level.

Q20 is linearised by a 680Ω emitter resistor for a more progressive action (no additional Miller capacitor is needed). A 2.2kΩ collector resistor (from ground) limits the current delivered to Q25 under a hard short-circuit condition and thus limits the dissipation in Q25. Diode D12 protects the circuit in case an external load pulls the output terminal negative.

Remaining circuitry

The regulator's positive rail is labelled VPP and comes from the charge pump described last month (see Fig.3). This tracks VIN and is generally boosted to be 10V higher. VEE is a regulated –5V rail, derived from the same charge pump. These supply rails are 'wider' than the input supply (VIN) and ensure that Q23's gate can vary over a wide enough range (approximately 0-43V) to control the output over the full range of 0-40V.

There are a couple of aspects of this circuit which are not obvious at first glance. The top end of the 0.1Ω current-sense resistor is connected both to 'VOUT-' and 'CurrSense'. The former is for return current to flow from the load while the latter goes to the ammeter divider circuit. This sense resistor can dissipate up to 2.5W at 5A; its value was chosen as a compromise between keeping the dissipation reasonable and giving enough of a voltage swing for the current-limiting circuitry to operate quickly and accurately.

In addition, the non-inverting input for voltage regulation (Q14's base) is connected to the top of this resistor (ie, CurrSense) rather than to ground as you might expect. This is because we don't want the output voltage to drop as the load current increases due to the increase in voltage across the current sense resistor.

This connection for Q14, in combination with the fact that the output divider's –2.5V reference is also connected to the top of this sense resistor (via Vout–; see Fig.3 last month), means that the voltage as set by VR1 is actually VOUT+ – VOUT-. As a result, when VOUT- increases, so must VOUT+ due to the negative feedback action.

Minor changes

Since publishing the main circuit diagram last month, we have made a few minor changes to the circuit. First, we added a 100µF bypass capacitor at the input of REG2, as the latter was moved away from REG1 and its 100µF output filter capacitor to aid heat dissipation.

We also increased the value of the 2.2MΩ resistor (near VR8) to 10MΩ and reduced the associated 1kΩ resistor to 680Ω, so that the ammeter reads zero when there is no current flow.

In addition, the 680Ω resistor connected to VR5 has been changed to 820Ω to ensure that the maximum current can be set to 5A.

Finally, the 1kΩ resistor at the ground end of VR7 has been reduced to 820Ω, although if you link out VR7 as suggested, either value will work.

Building it

Despite the circuit complexity, the assembly is quite straightforward. All the parts are mounted on a PCB coded 18104141 and measuring 198 × 95mm. This PCB is available from the *EPE PCB Service*. Fig.7 shows the parts layout and external wiring details.

It's easiest to fit all the surface-mount (SMD) parts on the PCB first, starting with IC1. Begin by removing it from its packaging and locating the pin 1 dot (which isn't all that obvious).

If using a hot-air station or reflow oven, it's simply a matter of sparingly applying fresh solder paste to the pins

The PCB fits neatly inside this standard instrument case which comes complete with 3.5-digit LED readouts for simultaneous voltage and current display. The final assembly details are in Part 3 next month (prototype PCB shown).

and central pad, placing the IC with the dot at lower-left and then heating the device until the joints are formed. Or, provided you have a temperature-controlled soldering iron with a fine bit, you can certainly do it by hand.

The procedure for hand-soldering IC1 is as follows. First, it's a good idea to place a blob of flux gel on the central pad. This helps hold the IC in place during soldering and will also come in handy when it's time to solder the thermal pad. That done, put a very small amount of solder on one of the pads, check that its orientation is correct, then heat this solder and slide the IC into place.

Now check that all the pins are correctly aligned with their pads using a magnifying glass. Each pin should be on top of its associated pad and not protruding over the side. Unless you're very lucky, it won't be right the first time, in which case you need to reheat the single soldered pad and give the IC a gentle nudge in the right direction. Repeat this procedure until you're happy with the placement, then solder the diagonally opposite pin and re-check the orientation.

Having tacked it down, you now have several possibilities for soldering the remaining pins. You can solder two or more pins at a time by placing a standard chisel/conical tip between a pair of pins and feeding a small amount of solder in (pre-fluxing the pins helps) or you can run flux down both sides of the IC and then drag solder all the pins in one go using a hoof or mini-wave tip (this can also be done with standard tips but not as easily). In either case, using a high-quality flux paste makes the process a lot easier.

Don't worry if any or even all the pins are bridged after soldering; it's just a matter of applying some more flux paste, placing some solder wick over the bridge and then heating it until it 'sucks up' the excess solder. Just be careful not to pull on the wick or otherwise apply force until the solder has melted or you could damage the IC pins or the board.

Once the chip is in place, flip the board over and apply some liquid flux or flux gel to the three vias under IC1. Now melt some solder into these holes; there is an exposed pad surrounding them to make it flow better. The combination of capillary effect and flux on both sides of the board should cause the solder to flow through and form a joint between the IC and the pad on the other side. You can confirm this is the case by touching the IC after doing this; it should be quite hot due to the solder that's adhered to its thermal pad.

Finally, clean off any flux residue or other contaminants using a good solvent and then carefully examine the joints using a magnifying glass and lamp to ensure that every pin has been soldered to its pad and no bridges remain.

(Note: if you have to remove this IC, it's easy to do using a hot-air gun (which can be bought quite cheaply). It's virtually impossible to do using any other method, without damaging the board.)

SMD MOSFETs

These are next on the list. Again, you can use solder paste and hot air/reflow; however, these can also be soldered using a regular iron. Put some flux on the large PCB pad for the tab and then flow a small amount of solder onto it. Ensure this forms a thin, even layer on the pad; if not, clean off the excess using solder wick.

Now do the same to the underside of the MOSFET tab itself; you will probably have to place it in a mini vice or some other clamp while doing so.

Next, spread some flux paste onto the tinned PCB pad, then put a small amount of solder onto one of the four smaller mounting pads on the PCB. It's easiest to start with the topmost (Q2) or right-most (Q3) pad (ie, the MOSFET gates) as these have the least thermal mass.

As with IC1, heat this solder and slide the MOSFET into place, then check that its tab and remaining pins are properly centred on their pads. You can now apply a little flux along the edge of the large tab and heat it with your soldering iron until the layers of solder on both melt and merge.

That done, it's just a matter of letting it cool a bit, soldering the three remaining pins, then touching up the gate joint (ie, the first small pin you soldered) using a bit of extra flux.

You can now use a similar procedure to fit inductor L1, ie, tin the underside of its leads, tin the PCB pads, add flux to both, then flow them together. Press down gently on the inductor while soldering the second pad and then re-flow the first one to ensure it's right down on the board. Note that it might be necessary to add more solder to the initial pad, to form a good joint. That's the easiest method we've found to solder such a large SMD component.

While doing this, you will need to hold it with tweezers or similar as it gets hot. Use this same technique to fit diodes D1 and D2, but be careful with their orientation; their cathode stripes face in opposite directions.

Now fit the remaining SMD capacitors and resistors. For each, it's just a matter of placing solder on one of the pads, sliding the part in, waiting for the joint to cool and then soldering the other side. Be careful – it's quite easy to get solder to flow onto the part but not the PCB pad; use plenty of flux, clean off the residue and inspect the joints carefully under magnification.

Note that the resistors will be labelled with their value (eg, 15kΩ = 153, 10Ω = 100). On the other hand, the ceramic capacitors are not labelled and you will have to check the value on the packaging before removing them. Note also that there are some SMD components away from the switch-mode section. These are the two additional 4.7µF ceramic capacitors near lower-left and lower-right and the 0.1Ω shunt near the negative output terminal. You can use a through-hole shunt instead of an SMD type, if you can get one with that will fit and has the correct rating.

Now is also a good time to solder in the three BCM856DS dual transistors (assuming you are using these, as recommended). Their pin layout is symmetrical so orientation doesn't matter. You may be able to solder the pins individually, then clean up any bridges with flux paste and solder wick. In fact, we like to add some flux and apply solder wick anyway as reflowing the joints in this manner gives a more consistent and reliable result.

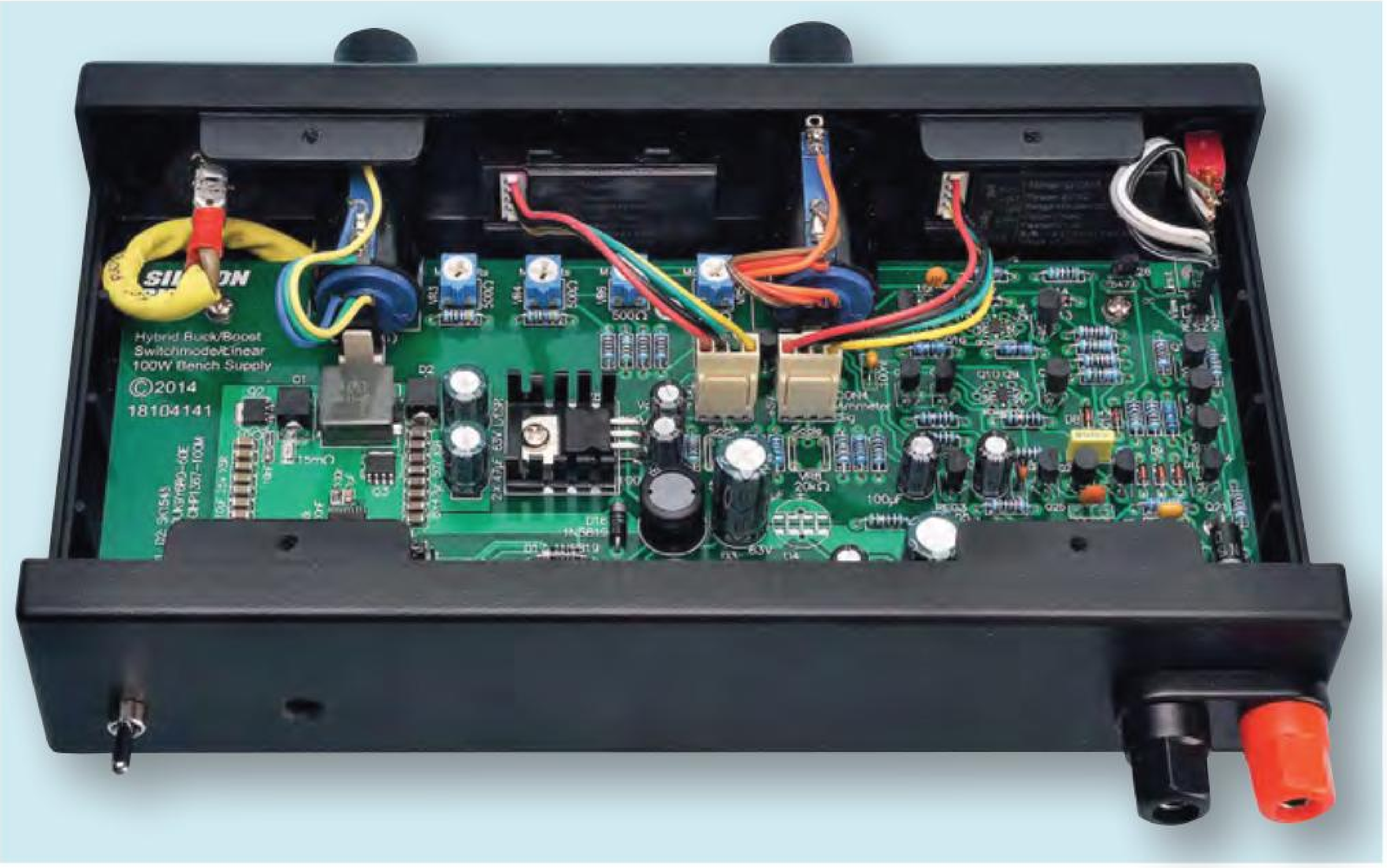
Through-hole parts

With the SMDs out of the way, the next job is to fit the passive through-hole components, starting with the 1N4148 diodes. Note that these do not all have the same orientation, so check the layout diagram (Fig.6) carefully. Follow with the resistors (check the values with a DMM if unsure) and then the medium-sized diodes such as the zeners and 1N5819s, again taking care with the orientation.

Leave 27V zener diodes ZD2, ZD5 and ZD6 out for now. Diode D12 (1N5404) should also be left out at this stage.

Now solder IC2 in place (don't use a socket), making sure that its notch or dot faces towards the top. Follow with ferrite bead FB3 (FB1 and FB2 were removed from the design). If you have a plain bead without leads, run a component lead off-cut through it.

The next job is to fit Q1. First, bend its leads down through 90° about 6mm down from the tab, then feed them through and fasten its tab down using an M3 × 6mm machine screw and nut. Solder and trim the leads, then install all the ceramic capacitors, including the multi-layer types, followed by the MKT capacitors.



Another view inside the case, this time from the rear. The rear panel carries the power switch (S1), a hole to access the DC socket and the two output terminals (note: prototype PCB shown).

That done, fit the zener diodes you left out earlier (ZD2, ZD5 and ZD6) but space these off the board by about 5mm to allow the air to circulate beneath them for cooling (they get hot if they conduct a significant amount of current). Next come the trimpots; remember that you probably don't need to fit VR7 and VR8 but if you do, VR8 should be the 20kΩ pot. If you aren't fitting them, each should have two wire links soldered in its place where shown.

You can now install the pin headers for LK1, LK2 and S2, followed by the two fuse clips. Check that these have the retaining lugs on the outside or the fuse will not fit and make sure they are fully inserted before soldering.

Next on the list are all the TO-92 devices, ie, the small signal transistors plus REG3 and REG4. Check their markings to ensure each one goes in the right place and bend the leads with small pliers if necessary, so that they fit the PCB pad layout. Note that if you are not using the BCM856DS chips, you will also need to install BC556s for Q4, Q5, Q9, Q10, Q14 and Q15. Be sure to smear thermal paste on the faces of these transistors and push each pair together so that they are in close contact.

The remaining diode (D12) can go in. It too should be spaced off the board by about 5mm. Follow this with the smaller electrolytic capacitors (47µF and 100µF), all of which are inserted with the positive (longer) lead towards the top of the board. The two bobbin inductors (L2 and L3) and the DC socket (CON1) can then go in. Be sure to push the latter all the way down onto the PCB before soldering.

Now for the heatsinked TO-220 devices, ie, REG1, REG2 and Q23. Don't get these mixed up; they are installed in the same manner as Q1 except that you will need to slide the heatsink under the device package before fastening each assembly down using an M3 x 6mm machine screw and nut. If you like, you can smear some heatsink paste on each device tab before its fastened down, although this isn't strictly required.

Finally, complete the PCB assembly by fitting the power switch (S1), polarised connectors (CON3-CON6) and the two 220µF electrolytic capacitors. If you're using a through-hole shunt, don't forget to install that too.

Next month

That's all we have space for this month. In the final article next month, we'll run through the test procedure and the trim adjustments, describe how to build it into the case and give some tips on using it.

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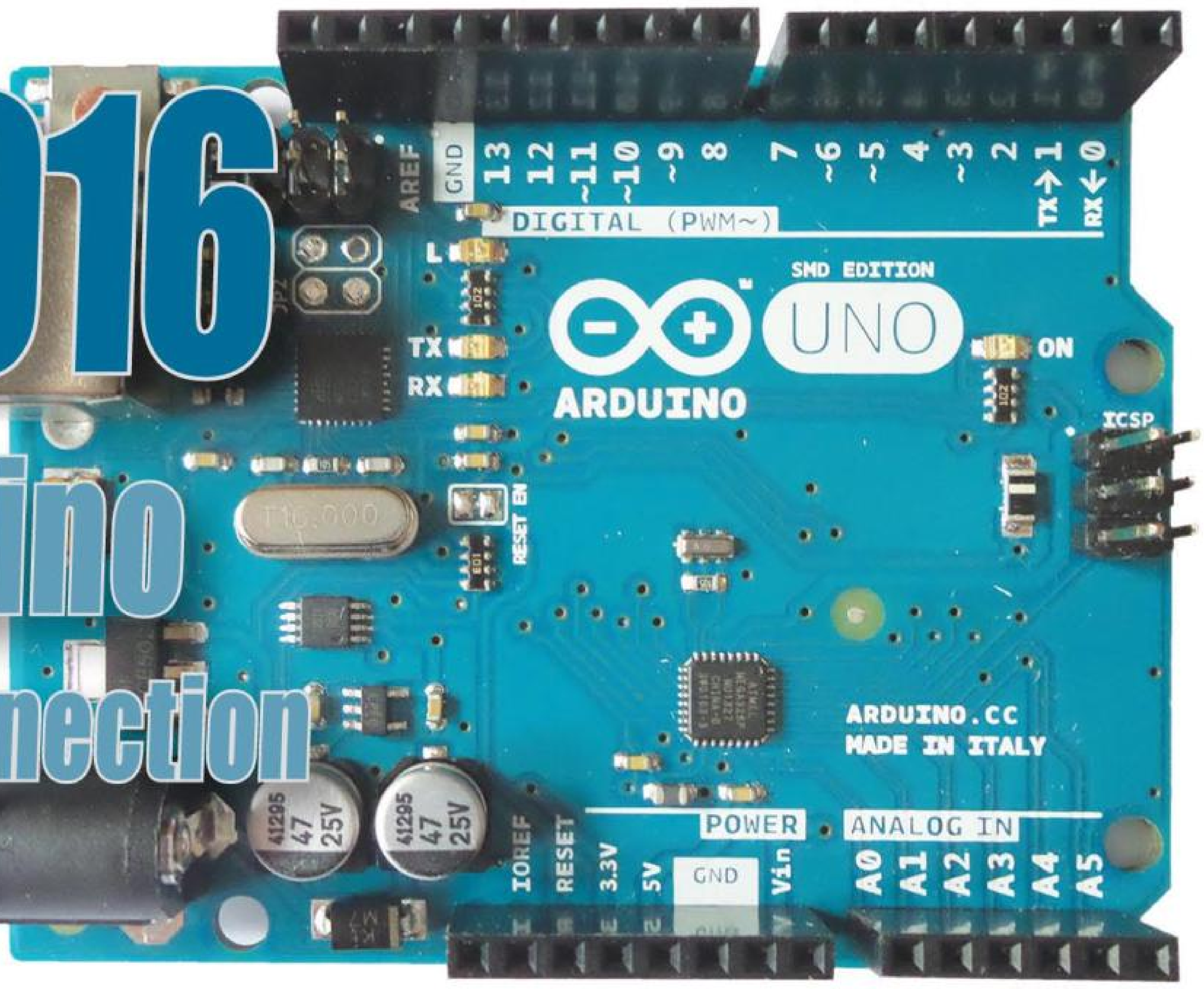
Teach-In 2016

Exploring the Arduino

Part 9: LAN and Internet connection

by Mike and Richard Tooley


AREF
GND
13
12
~11
~10
~9
8
7
~6
~5
4
~3
2
TX→1
RX←0
DIGITAL (PWM~)
L
TX
RX
SMD EDITION
UNO
ON
ARDUINO
ICSP
RESET EN
ARDUINO.CC
MADE IN ITALY
IOREF
RESET
3.3V
5V
GND
Vin
POWER
ANALOG IN
A0
A1
A2
A3
A4
A5

Welcome to *Teach-In 2016 – Exploring the Arduino*. This exciting new series has been designed for electronics enthusiasts wanting to get to grips with the immensely popular Arduino microcontroller, as well as coding enthusiasts who want to explore hardware and interfacing. So, whether you are considering what to do with your Arduino, or maybe have an idea for a project but don't know how to turn it into reality, our new *Teach-In 2016* series will provide you with a one-stop source of ideas and practical information.

In last month's *Teach-In 2016, Arduino World* we continued our infra-red (IR) theme by looking at how IR remote control can be added to your Arduino Uno and Nano projects. *Arduino Workshop* introduced you to IR transmitters and receivers, and our programming feature, *Coding Quickstart*, investigated the Arduino's versatile IR remote library. As usual, we concluded the instalment with a *Get Real* project, this time featuring the design and construction of an Arduino multi-channel IR remote controller allowing you to control your lighting, heating, doors, windows and a host of other gadgets from the comfort and security of your armchair.

This month

In this month's *Teach-In 2016, Arduino World* will be looking at methods of connecting an Arduino to a local area network (LAN) and to the Internet using an Arduino Ethernet shield. *Arduino Workshop* will introduce you to the practical aspects of using Ethernet linking to send and receive data using a standard router or hub fitted with an Ethernet port. Our programming feature, *Coding Quickstart*, looks at the Arduino's comprehensive Ethernet library. Finally, our *Get Real* project feature describes the design and construction of a highly accurate Internet-connected digital clock.

Arduino World: Connecting to a LAN

The easiest way of connecting a basic model Arduino (such as an Uno) to the rest of the world is with an Ethernet shield and a hard-wired connection to a network hub or router. Later in this series we will be looking at the use of wireless as an alternative to a hard-wire network connection; but, to keep things as simple as possible, we will start with this well-tried solution to the problem of connecting to the outside world.

Ethernet

First entering service more than thirty years ago, Ethernet is still the most widely used local area network (LAN) technology. A device with an Ethernet port is able to exchange data with a similarly equipped device, a local area network, or with a DSL or cable router. The standard (defined in IEEE 802.3) was originally designed for speeds of 10Mbps but was enhanced to support higher bit rates and longer link distances (up to 100Mps with a typical maximum cable run of about 100m). For longer distances it is possible to bridge networks together making it possible to have a local area network (LAN) over the area occupied by a large school, college or factory site. A network bridge is a relatively small and simple device.

Ethernet operates at both the physical layer (Layer 1) and the data link layer (Layer 2) of the OSI network protocol model (see Fig.9.1). It defines two transmission units, packet and frame (the latter includes the data being transmitted as well as addressing information relating to both the sender and receiver of the data). Each frame is contained within a package, which adds the information necessary to establish the connection and also to indicate where the frame starts.

Data encoding

Data is transmitted in Manchester-encoded format (see last month's Teach-In) and sent in a series of packets. The maximum payload that can be sent in a packet is 1500 bytes, so longer sequences

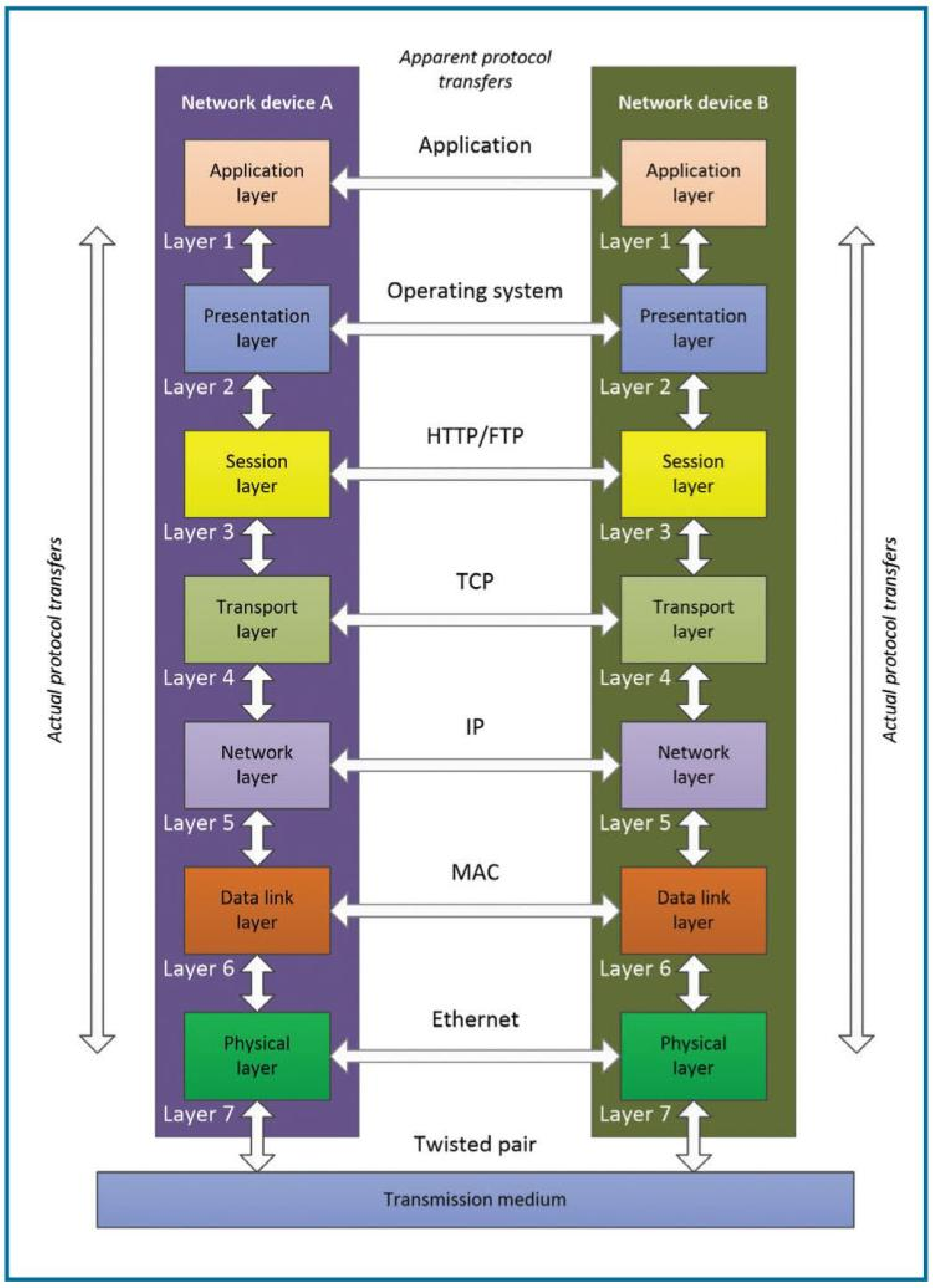

Apparent protocol transfers
Network device A
Network device B
Application
Application layer
Application layer
Layer 1
Layer 1
Operating system
Presentation layer
Presentation layer
Layer 2
Layer 2
HTTP/FTP
Session layer
Session layer
Layer 3
Layer 3
TCP
Transport layer
Transport layer
Layer 4
Layer 4
IP
Network layer
Network layer
Layer 5
Layer 5
MAC
Data link layer
Data link layer
Layer 6
Layer 6
Ethernet
Physical layer
Physical layer
Layer 7
Layer 7
Twisted pair
Transmission medium
Actual protocol transfers
Actual protocol transfers

Fig.9.1. ISO model for Open Systems Interconnection (OSI)

Table 9.1 Ethernet packet fields

Field name	Length (bytes)	Function
Preamble	7	Synchronisation (a leading string of alternate 0s and 1s in the preamble enables clock synchronisation)
Start of frame delimiter (SFD)	1	The SFD (a single byte comprising 1101010) marks the start of the frame.
Destination address	6	MAC address of the packet's destination. Some addresses are reserved or have special functions (for example, allowing a network-connected device to broadcast data to all nodes simultaneously)
Source address	6	MAC address of the source of the data. The MAC address is unique to a particular device and is usually built-in during manufacture and printed on the device. In many cases, the first group of three bytes are used to identify the manufacturer and the second group of three bytes relate to the particular item
Type/length	2	Indicates the length of the frame or the type of data present in the data field that follows. If the value is less than 05DC hex it represents the length of the data field. If the value is greater than 0600 hex then it represents the type of protocol in the data field
User Data Field (UDF)	46 to 1500	The UDF contains the client data to be transported, including protocol and passing (see text)
Frame Check Sequence (FCS)	4	The FCS is calculated for the entire frame and appended to the frame. The FCS is calculated during transmission and again upon reception. If the received FCS differs from the transmitted FCS the frame is discarded or 'dropped'

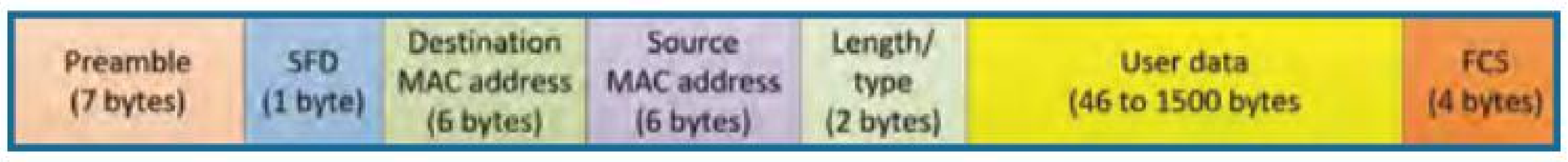

Preamble (7 bytes)
SFD (1 byte)
Destination MAC address (6 bytes)
Source MAC address (6 bytes)
Length/ type (2 bytes)
User data (46 to 1500 bytes)
FCS (4 bytes)

Fig.9.2. General format of an Ethernet packet

need to be broken down into smaller segments before transmission.

The general arrangement of an Ethernet packet is shown in Fig.9.2. The minimum length of the user data field is 64 bytes and if the field is shorter than this then extra padding data will be added. The functions of the various fields within the Ethernet packet are summarised in Table 9.1.

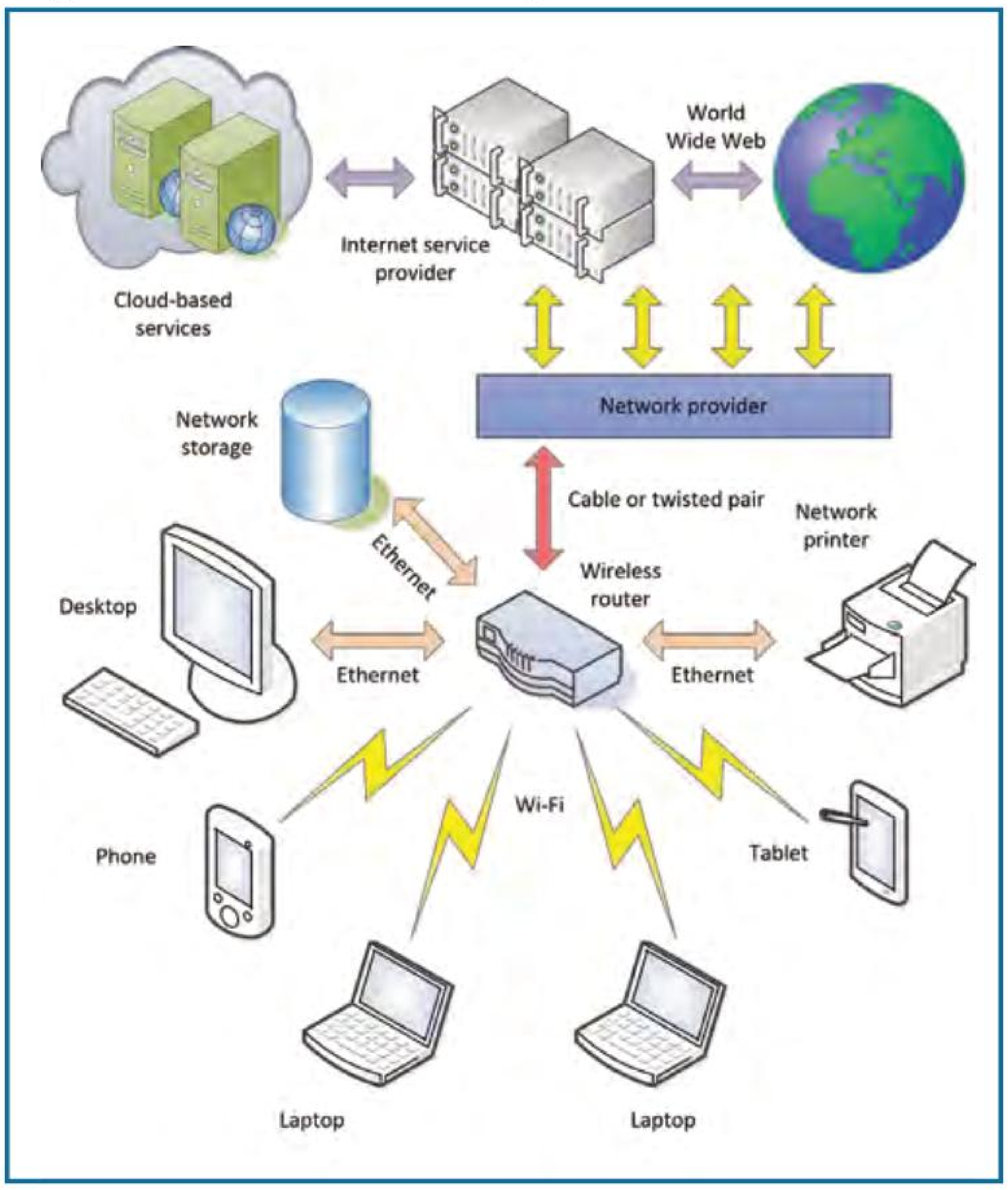


Fig.9.3. Typical local area network where devices are connected to a router with Ethernet cables and Wi-Fi.

User data

In addition to the maximum data size (1500 bytes) there is also a minimum amount of data that can be present within the UDF. Valid frames must contain at least 46 bytes of data. If there's less than this then padding is used until the minimum size is achieved. The upper limit on the size of the data field is designed to ensure fair access and availability to other network users in the gaps between packets.

Local area networks

Most small networks, including those used in the home and for small business, support both Ethernet connections and Wi-Fi, as shown in Fig.9.3. Depending on the available telecommunications infrastructure, the connection to the network provider can be made via conventional copper twisted pair, cable or fibre. The network provider provides a connection to the Internet service provider (ISP) and from there, via a wide area network (WAN) to the Internet so that network-connected services can access resources available from the World Wide Web and also from cloud-based services.

In order to facilitate the exchange of data between devices connected to a network there needs to be an established set of rules or a protocol. Two different protocols contribute to the basic set of rules used on the Internet: Internet Protocol (IP) supports both Transmission Control Protocol (TCP) and User Datagram Protocol (UDP). TCP requires an established connection between a client and a server. Once the connection has been explicitly established data can be sent in both directions. We refer to TCP as a 'connection-oriented protocol'. UDP, on the other hand, is simpler and is 'connectionless' because messages are transmitted without the ongoing handshaking required to support TCP data exchange. Usefully, the Arduino's Ethernet shield (and its associated library software) can support either of these methods.

UDP supports error detection via a checksum. However, when an error is detected, the packet is simply discarded and there is no attempt to resend the data. TCP uses both error detection and error recovery such that when a TCP checksum error is detected there will be no acknowledgment from the receiver. The sender will then retransmit the data until it is eventually acknowledged. TCP is therefore essential when there is a need for reliable data transfer, while UDP is best suited to transferring large blocks of data in a short interval of time.

Arduino Workshop: The Arduino Ethernet shield

Having explained some of the basics of networking, it is now time to put things into practice! A typical Ethernet shield for the Arduino Uno is shown in Fig.9.4. As with other shields, the expansion board fits neatly over the Uno and provides access to the usual digital and analogue I/O bus lines as well as power and ground connections.

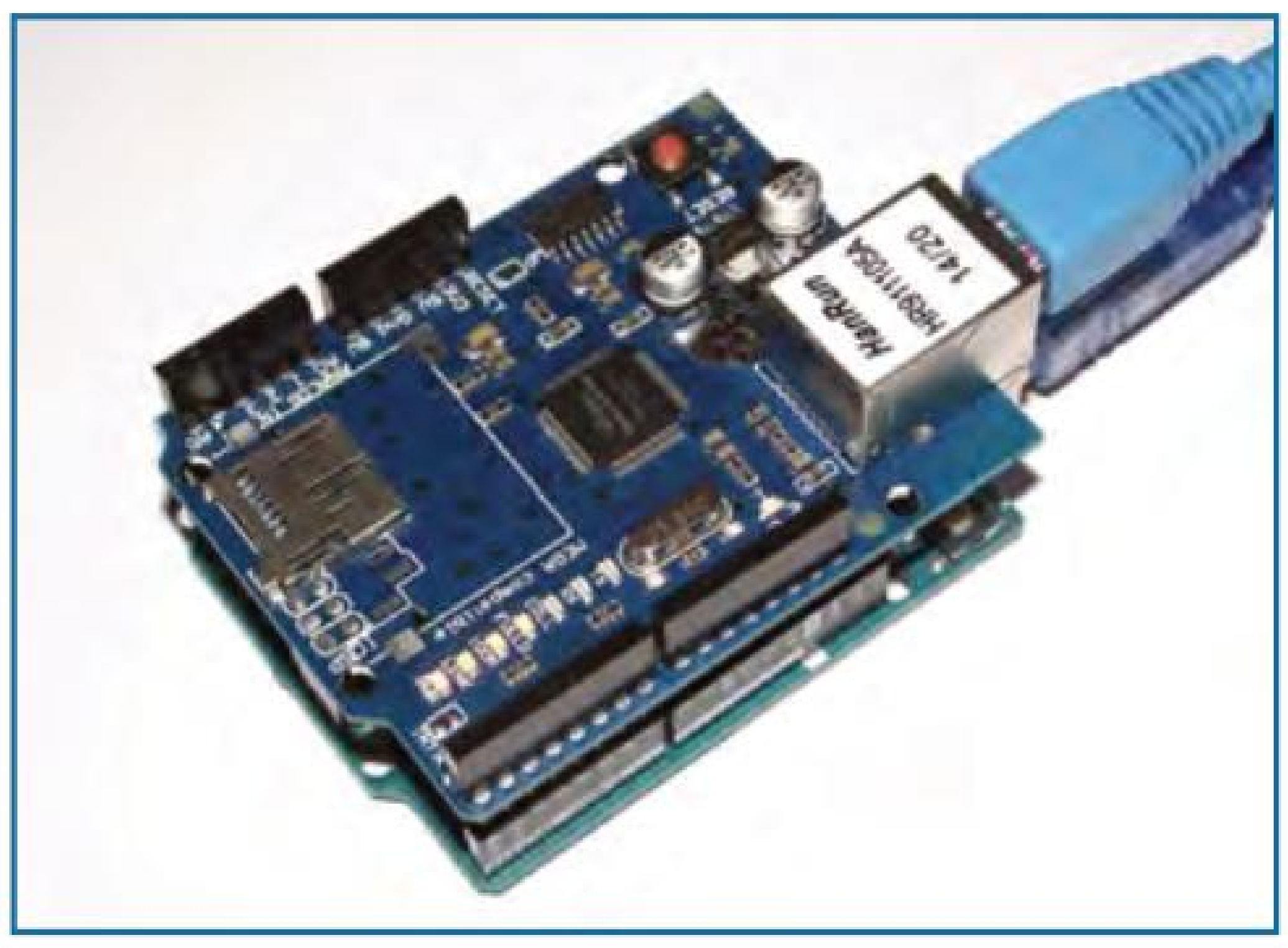


Fig.9.4. A typical Ethernet shield for the Arduino Uno

Table 9.2 Ethernet SPI bus connections

SPI bus function	Abbre-viation	Arduino digital I/O pin
Slave Select	SS	10
Master Out Slave In	MOSI	t11
Master In Slave Out	MISO	12
Serial Clock	SCK	13
Slave Select (see note)	SS	4

Note: Digital I/O pin-12 is the Slave Select for the Ethernet controller, and pin-4 is the Slave Select for the SD card interface.

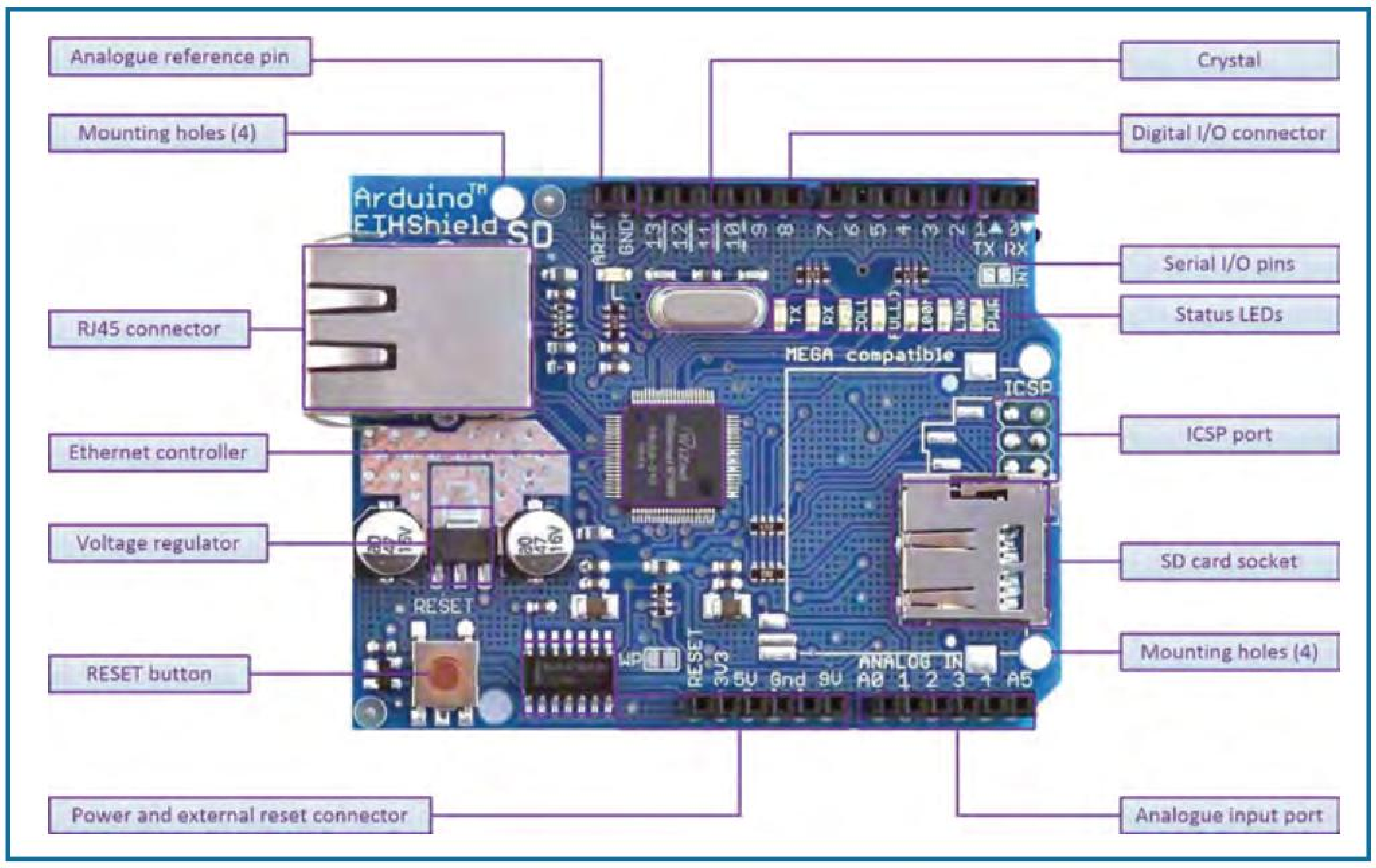


Figure 9.5 Main features of the Uno Ethernet shield

The main features of the Uno Ethernet shield are shown in Fig.9.5. Notice the RJ45 connector at the top left of the diagram. This provides connection, via three twisted pairs to an Ethernet port on a router or hub. The shield derives its power from the Uno, so no additional power connector is fitted. When first released several years ago the original Ethernet shield for the Uno was rather expensive, but recently various clones have appeared and you can now purchase one for less than £10 from several suppliers and this now makes network-linked projects highly affordable.

SPI bus interface

The Arduino communicates with the Ethernet shield using the Serial Peripheral Interface (SPI) bus. The connections are shown in Table 9.2.

SD card

Most Ethernet shields also contain a small bonus in the form of an additional micro-SD card slot. To make use of the SD card you will need to use the SD library described in *Part 5* of *Teach-In 2016* (*EPE*, June 2016). Note that the SD card operates independently from the shield's Ethernet function and there is no need to populate the card slot in order to make use of the network connection.

RJ45 connector

The Ethernet shield connects to a local area network by means of a hard-wired twisted-pair Ethernet connection. This method of connection is cheap, robust, reliable and simple to set up. The connection is made by means of an RJ45 connector. This device is a little more complex than it looks as it contains an isolating transformer arrangement, like that shown in Fig.9.6. The connector is usually fitted with two small LED indicators that indicate the status of the data link.

Coding Quickstart : The Ethernet library

The Arduino's comprehensive Ethernet library provides you with a means of connecting an Arduino to a LAN in several different ways. Depending on your application, you might wish to configure your Arduino as either a client or server. If you have already set up a network connection for other equipment then you will be familiar with the 'client/server' relationship and other networking terms, but for those of you that might be newcomers to the process we've explained a few of the key terms in the boxed feature shown on the next page.

Ethernet library

The Arduino Ethernet library will allow you to connect an Ethernet shield to your local area network making it possible to exchange data with other network devices and also with the Internet via a router. The Arduino can be configured so that it serves either as a client receiving data from the network or as a server accepting data from the network. The library supports up to four concurrent connections configured as inputs, outputs or a combination of both. There are two classes; `EthernetServer()` and `EthernetClient()`.

Server class

This creates server objects that can send data to and receive data from connected clients (programs running on other computers or devices). The client class creates clients that can connect to servers and send and receive data. In addition, to support the transfer of UDP messages (see glossary) the library also includes the `EthernetUDP` class

Setting up the Ethernet shield

As with other popular Arduino Uno shields, the Ethernet shield is simply mounted on top of the Uno board and plugged in. The shield will have a standard RJ45 connector and this will need to be connected to a hub or router using a length of CAT5 cable fitted with standard RJ45 connectors. The Uno (not the shield) will also require a USB cable connection so that code can be uploaded to it in the normal way. Once the code has been uploaded (and is working correctly!) the Uno and Ethernet shield can be powered from an external DC source (typically 9V DC) as usual. The

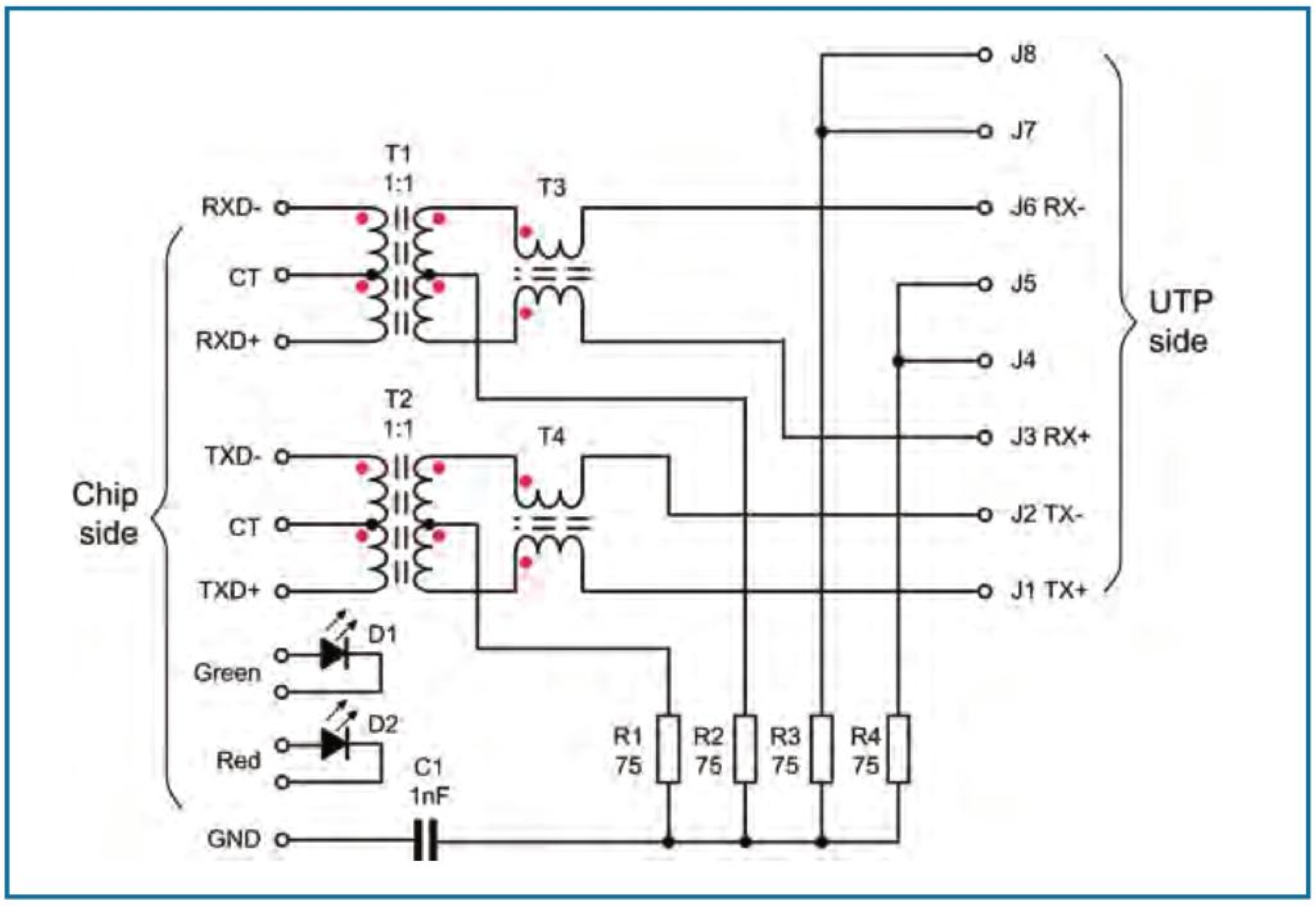


Fig.9.6. Connection to Ethernet universal twisted pair (UTP) transmission medium

Networking glossary

Checksum
A value produced by carrying out a mathematical operation on transmitted or received data in order to check the integrity of the data. The checksum of received data is computed and compared with the transmitted checksum. If the two values are not identical this indicates that an error has occurred.

Client
A device (eg, a PC) that requests services from another device – a server.

Dynamic Host Configuration Protocol (DHCP)
DHCP is a protocol that simplifies the connection of a device to a network. With DHCP, IP addresses can be allocated automatically. For example, a device can use DHCP to request an IP address from a router. This address can then be used for subsequent data interchange with other network-connected devices.

Domain Name System (DNS)
DNS is a means of substituting meaningful names for numerical IP addresses. When you enter a domain name like **www.epemag.com** into the address field of your browser a DNS server will request access to the *EPE Magazine* server (IP address **178.16.224.121**) saving you the effort of having to remember a sequence of numbers.

Gateway
A device that routes traffic between networks. For example, at home, your router acts as a gateway between your home network and the Internet.

Hypertext Transfer Protocol (HTTP)
HTTP is the standard protocol used to exchange data between a web browser and resources on the World Wide Web.

Internet Protocol (IP)
IP is the protocol that manages the exchange of data on the Internet. Each device connected to the Internet must be allocated a unique IP address. When a device needs to connect to another device it makes a connection to that device's IP address.

Local Area Network (LAN)
A local area network is a network that operates over a relatively small area; eg, a home, school, or business.

Media Access Control (MAC)
MAC is a communications protocol that distinguishes specific devices by means of a unique MAC address. Some devices are allocated a unique MAC address during manufacture, while others can be allocated a MAC address by means of programming software.

Network
The complete infrastructure that supports data interchange between a number of participating devices such as computers, printers, routers and gateways.

Node
A network-connected device that can initiate and respond to communication from other networked devices by means of a shared protocol.

Open Systems Interconnection (OSI)
OSI defines the standards used for open networking systems. The OSI seven-layered model uses seven different layers that indicate the peer-to-peer relationship that exists between participating devices (see Fig.9.1).

Packet
A basic (indivisible) unit of data sent between devices.

Port
A means of distinguishing the source/destination of network traffic by means of numbered ports (ranging from 1 to 65535). A web server will 'listen' on a specific port (usually port 80) for a request generated by a client.

Protocol
Protocols are a shared set of rules for communicating over a network. Different protocols are ideal for different types of communication. For example, HTTP is used for sending and receiving web pages, while FTP (file transfer protocol) is used for sending and receiving files.

Router
A device that manages network traffic between a number of devices.

Server
A device that supplies data, made available to, and shared by several users of a network.

Transmission Control Protocol (TCP)
TCP is a connection-oriented protocol in which a message makes its way across the internet by means of a stream of bytes from a server to a client and vice versa.

User Datagram Protocol (UDP)
UDP is a simple protocol used to transfer data between devices connected to a network. UDP requires no handshaking to control the exchange of data.

Uniform Resource Locator (URL)
A URL is a unique web address, for example **http://www.epemag.com**, which instructs a browser to use HTTP to connect to the server at *EPE Magazine*. When the address is entered, the DNS server will determine the IP address and the connection will be made using the default port (80).

Wide Area Network (WAN)
A WAN is a large network that operates over an appreciable area. A connection to the Internet usually involves connecting first to an Internet Service Provider (ISP) and then to the Internet.

Ethernet shield will require an additional supply current of around 50mA.

Addressing the Ethernet shield

The Ethernet shield must have a MAC (media access control) address assigned to it. This process allocates a unique physical address to the shield so that it can be distinguished from all other devices connected to the network. The MAC address comprises six consecutive bytes of data, also called a physical address, which is a unique identifier assigned to network interfaces for communications on the physical network segment. MAC addresses are used as network addresses for most IEEE 802 network technologies, including Ethernet and Wi-Fi.

Within your code, the MAC address is assigned using a fixed IP address and the `Ethernet.begin()` function. Some (but by no means all) Ethernet shields are supplied with a label indicating the MAC address that should be used. With other Ethernet shields you should find it possible to allocate your own address (note that this must *not* be the same as any other device connected to your network). Valid IP addresses depend on the configuration of your network. It is possible to use DHCP to dynamically assign an IP to the shield. Optionally, you can also specify a network gateway and subnet. You will find that the addresses quoted in sample applications will usually work without any change unless, of course, you have more than one Arduino Ethernet shield in use (in which case different MAC addresses are essential). Here's a typical code fragment used for assigning a MAC address.

```
byte mac[] = {0xDE, 0xAD, 0xBE,
0xEF, 0xFE, 0xED};

void setup() {
Ethernet.begin(mac);
}
```

Having defined the MAC address for your shield you will also need to allocate an IP address to it. This can be done manually (ie, as a fixed IP address) or it can be allocated dynamically as part of the set-up process each time you start your application. Which of these should you choose? A fixed or *static* IP address can be useful if you always need to have the same Internet address. On the other hand, a *dynamically allocated* IP address is useful because it takes into account what else is connected to your network.

Using DHCP

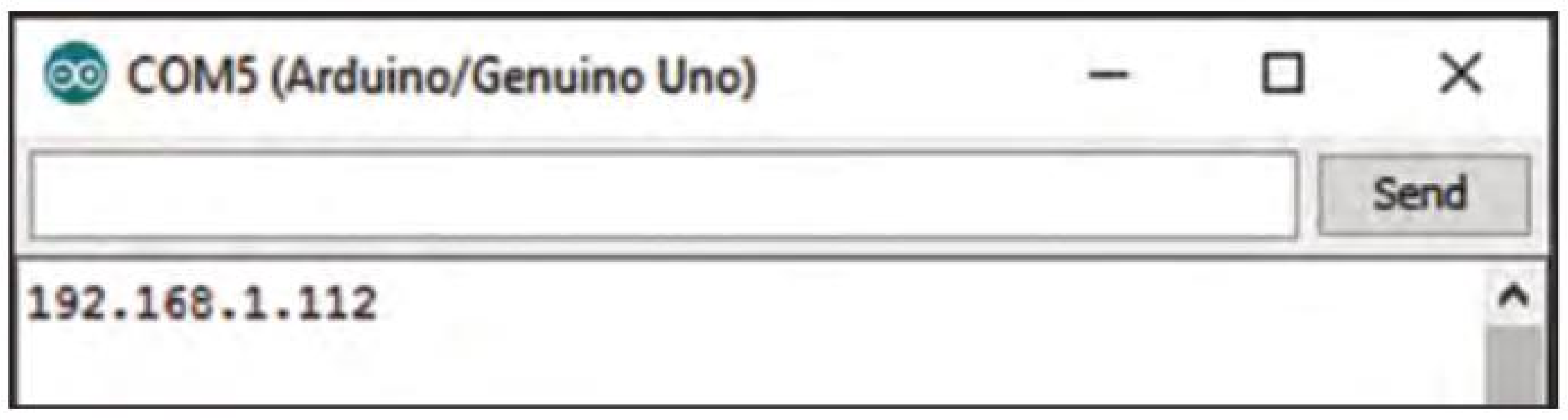
DHCP (or Dynamic Host Protocol) provides a network-connected host with a means of allocating local IP Configuration addresses. DHCP takes over the management of IP addresses within the network and you can use DHCP to request an address that you can then allocate to your device. The following code shows you how this is done. Having made the request to begin the Ethernet connection for the explicitly stated MAC address the server will display the allocated IP address using the Arduino's serial monitor (see Fig.9.7). In this case, the IP address allocated by the server is 192.168.1.112 but if you run the code a second time with a different MAC address you will obtain a different IP address.

```
// Obtain and display local IP address

#include <SPI.h>
#include <Ethernet.h>

// MAC address of the Ethernet shield
byte mac[] = { 0xDE, 0xAE, 0x00, 0xFF, 0xFE, 0x03 };

void setup()
{
  Serial.begin(9600);
  while (!Serial){};
  if (Ethernet.begin(mac))
  {
    Serial.println(Ethernet.localIP());
  }
  else
  {
    Serial.println("Unable to connect!");
  }
}

void loop()
{
}
```

If you need to use static IP addressing rather than DHCP, here's an example that shows how it's done. Notice that we've used `IPAddress()` to specify the address explicitly. However, as mentioned before, this address must be unique on your network and not be shared by any other devices present.

```
// Allocate static IP address to a server

#include <Ethernet.h>

// MAC address and IP address (see text)

byte mac[] = { 0xDE, 0xAD, 0xBE, 0xEF, 0xFE, 0xED };

IPAddress ip(192, 168, 1, 177);

// Initialize the Ethernet server library
// with the IP address and port you want
// to use (port 80 is default for HTTP):

EthernetServer server(80);

EthernetClient client;

char line1[100];
char buffer[100];

void setup() {
  Ethernet.begin(mac, ip);
  server.begin();
}

void loop() {
// Main code goes here
}
```

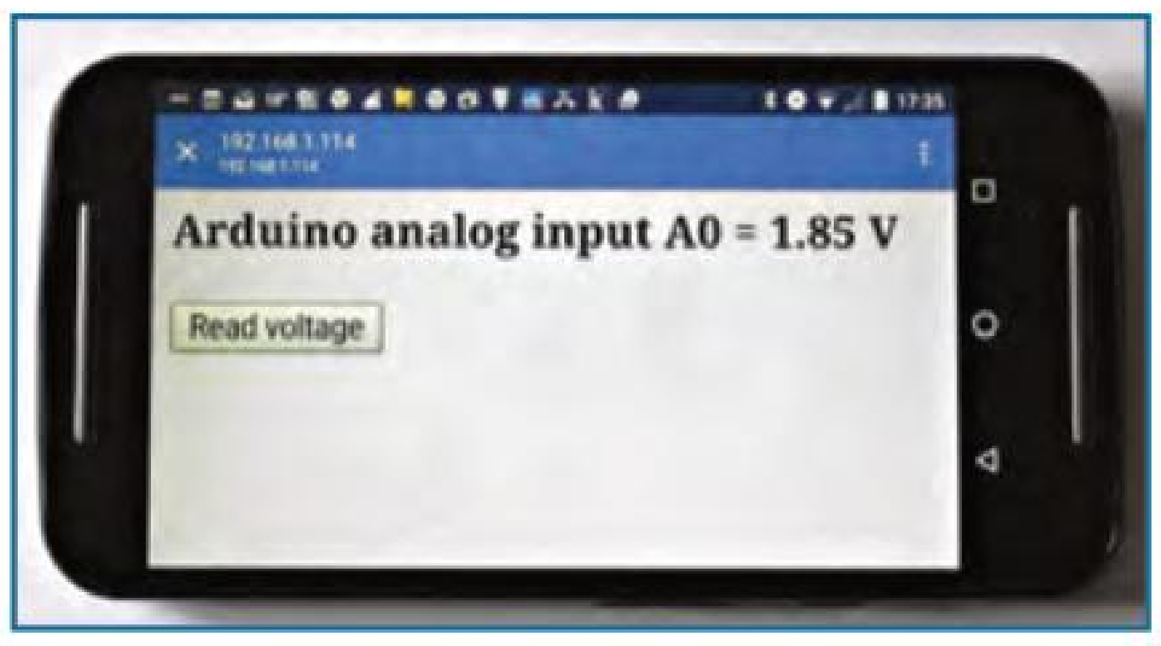
The previous block of code is something that you might want to include at the beginning of an application that uses the Arduino Ethernet shield to create a server making resources available to other connected devices. Listing 9.1 shows the major part of a web server application that makes the analogue voltage present on analogue input A0 available to other devices on the network. **Note this is not the complete listing.** Please visit the *EPE* Website at **www.epemag.com** to download the full code.



```
192.168.1.112
```

Fig.9.7. An IP address allocated using DHCP displayed using the Arduino's serial port monitor

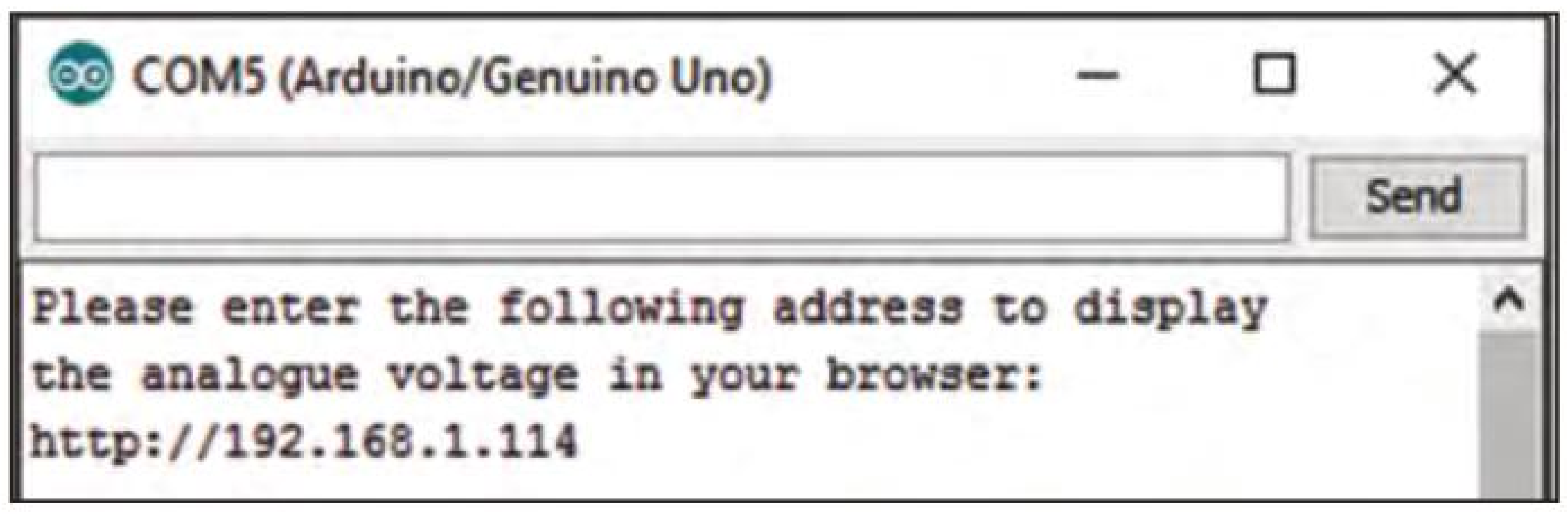
The typical result of running the code shown in Listing 9.1 is shown in Fig.9.8. This is the display from a mobile phone connected to the network using Wi-Fi. Note that the local IP address of the Arduino Ethernet shield has been entered into the browser's address field (in this case it is 192.168.1.114). Since this has been allocated dynamically (using DHCP) the address has been made available using the Arduino's serial monitor, see Fig.9.9.



Arduino analog input A0 = 1.85 V

Fig.9.8. Arduino-served web page displayed on a mobile phone

Listing 9.2 shows an example of using an Arduino as a web client. This example is similar to that shipped with the Arduino's Ethernet library (based on work by David Mellis, Tom Igoe and Adrian McEwen) but it has been simplified in several places. Since the Arduino doesn't have a web browser the web page specified in the code (see Fig.9.10) appears as HTML code displayed in the Arduino's serial monitor (see Fig.9.11).



```
Please enter the following address to display
the analogue voltage in your browser:
http://192.168.1.114
```

Fig.9.9. Using the serial monitor to determine the IP address of an Arduino-served web page displayed on a mobile phone

Get Real : Arduino Internet Clock

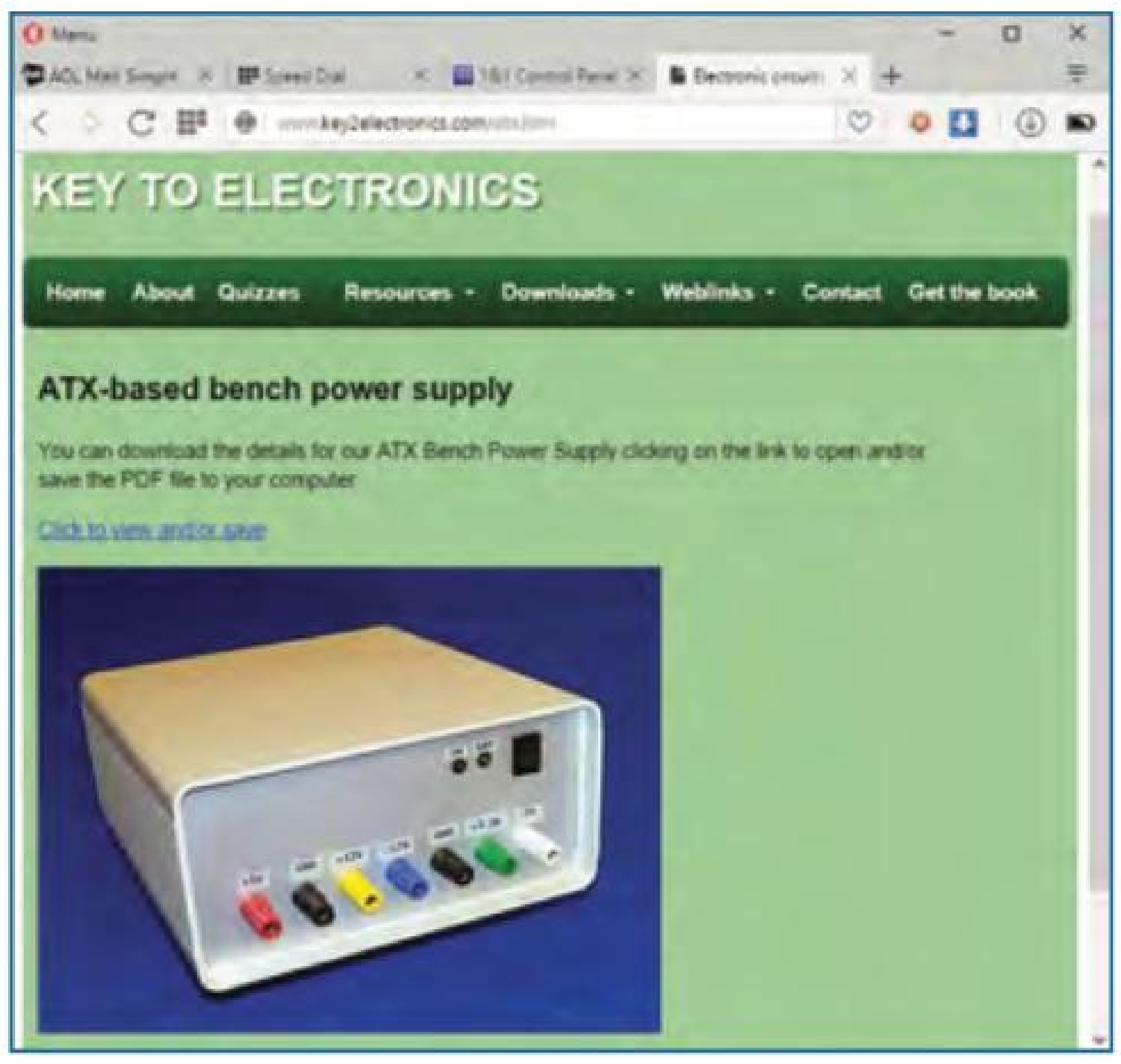
In this month's *Get Real* we will be using an Arduino with companion Ethernet shield as a web client configured to receive accurate time information from the internet, displaying it using a conventional LCD panel. The complete circuit of the Arduino Internet Clock is shown in Fig.9.12. In addition to the basic Arduino Uno, the clock comprises three modules. The first of these is a standard Ethernet shield that can be purchased from several suppliers in the UK and in the Far East. In addition to the Ethernet shield, the Arduino Internet Clock requires a standard 16-character × 2-line LCD panel. Since we wanted to reserve the digital I/O lines for possible future alarm functions we interfaced the display using a serial SPI interface rather than connect to the digital I/O ports. The SPI display interface can be purchased separately and then simply attached to the rear of the LCD display or it can be supplied ready-wired to the display. Since the cost savings were marginal we chose the latter approach.

You will need

Arduino Uno
Arduino Uno Ethernet shield
Ethernet cable (as required)
USB cable with miniature-USB connector (for programming only)

Listing 9.1 A simple web server application

```
// Web server displaying analogue voltage on A0

#include <SPI.h>
#include <Ethernet.h>

byte mac[] = { 0xDE, 0xAE, 0x00, 0xFF, 0xFE, 0x03 };
EthernetServer server(80);
EthernetClient client;

char line1[100];
char buffer[100];

void setup()  // use serial monitor to display the IP address
{
  Serial.begin(9600);
  if (Ethernet.begin(mac))
  {
    Serial.println(F("Please enter the following address to
display"));
    Serial.println(F("the analogue voltage in your browser:"));
    Serial.print(F("http://"));
    Serial.println(Ethernet.localIP());
  }
  else
  {
    Serial.println(F("Unable to connect to the network"));
  }
  server.begin();
}

void loop()
{
  client = server.available();
  if (client)
  {
    if (client.connected()) // prepare the HTTP header
    {
      readHeader();
      if (! pageNameIs("/"))
      {
        client.stop();
        return;
      }
      client.println(F("HTTP/1.1 200 OK"));
      client.println(F("Content-Type: text/html"));
      client.println();

      sendBody();
      client.stop();
    }
  }
}

void sendBody()  // create a web page using HTML
{
  client.println(F("<html><body bgcolor = #E6E6FA>"));
  sendAnalogReadings();
  client.println(F("<form method='GET'>"));
  client.println(F("<input type='submit' value='Read voltage'/>"));
  client.println(F("</form>"));
  client.println(F("</body></html>"));
}

void sendAnalogReadings()  // send analogue readings to the page
{
  client.println(F("<p><h3>"));
  client.println(F("Arduino analog input A0 = "));
  int analogueValue = analogRead(0);
  client.print((float) analogueValue/205);
  client.println(F(" V"));
  client.println(F("</h3></p>"));
}
```



ATX-based bench power supply

You can download the details for our ATX Bench Power Supply clicking on the link to open and/or save the PDF file to your computer

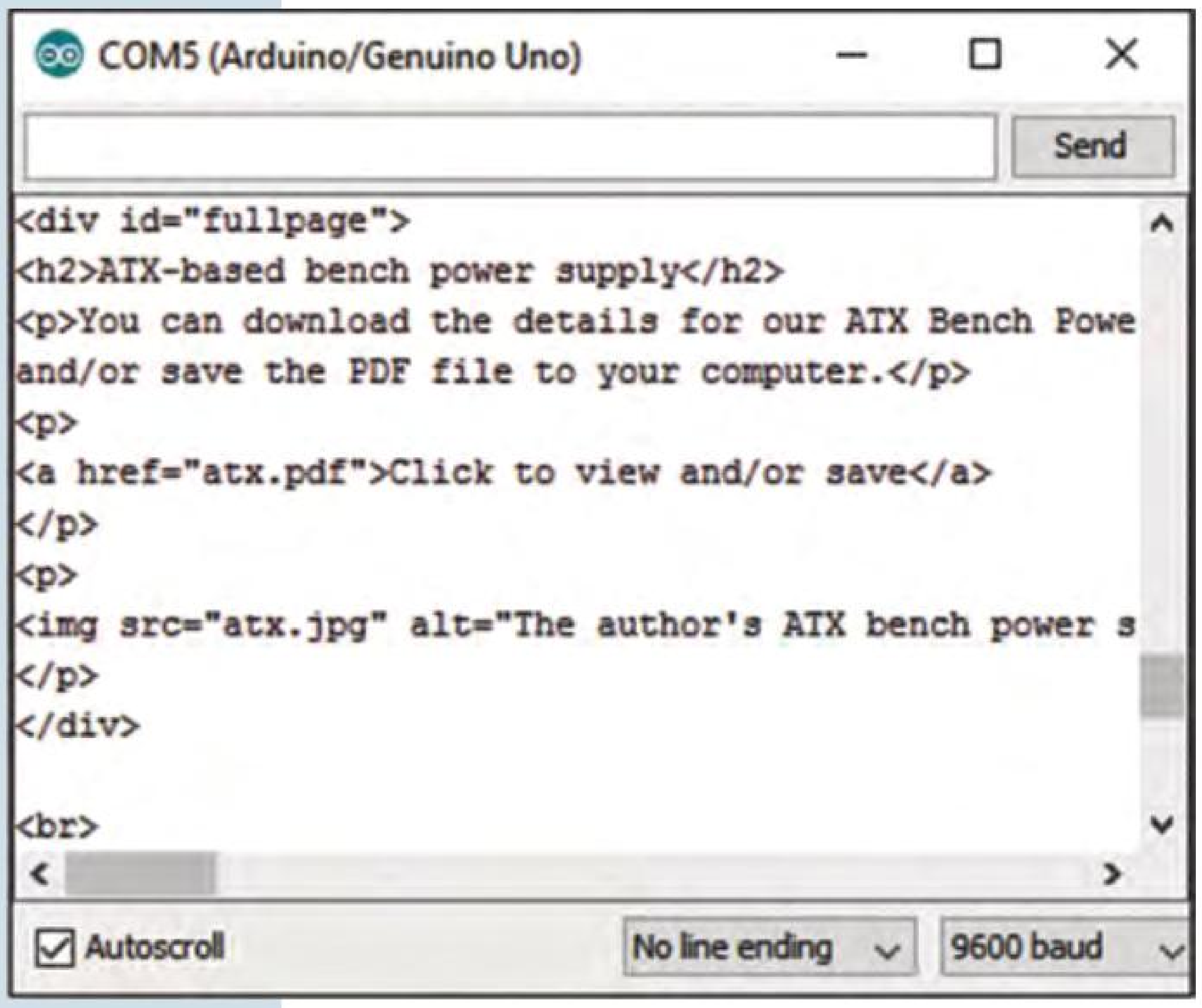
Click to view and/or save

Fig.9.10. The web page being accessed by the Arduino

Computer with an available powered USB port (for programming only)
16 × 2 LCD display with serial (SPI) interface

Code

Since the complete code listing for the Arduino Internet Clock would occupy several printed magazine pages we have only included some of the more important sections of code with added comments here. You can download the complete code from **www.epemag.com**. In order to obtain the address of an NTP time server from the pool of those available you can download and use Tom Igoe's time server application (also available for download from **www.epemag.com**). This will print the NTP address for you to use in your own code (see Fig.9.14).



```
<div id="fullpage">
<h2>ATX-based bench power supply</h2>
<p>You can download the details for our ATX Bench Powe
and/or save the PDF file to your computer.</p>
<p>
<a href="atx.pdf">Click to view and/or save</a>
</p>
<p>
<img src="atx.jpg" alt="The author's ATX bench power s
</p>
</div>

<br>
```

Fig.9.11. The web page in Fig.9.10 being displayed as HTML code using the Arduino's serial monitor

As with our previous *Get Real* projects, the code should first be entered into the IDE and then saved before compiling and uploading it to the Uno as described in last month's *Arduino Workshop*. When you have debugged and corrected your code don't forget to save it by clicking on 'File' and 'Save' or 'Save As…'. Next click on 'Sketch' and 'Verify/Compile'. Any compilation errors will then be reported in the window at the bottom of the IDE.

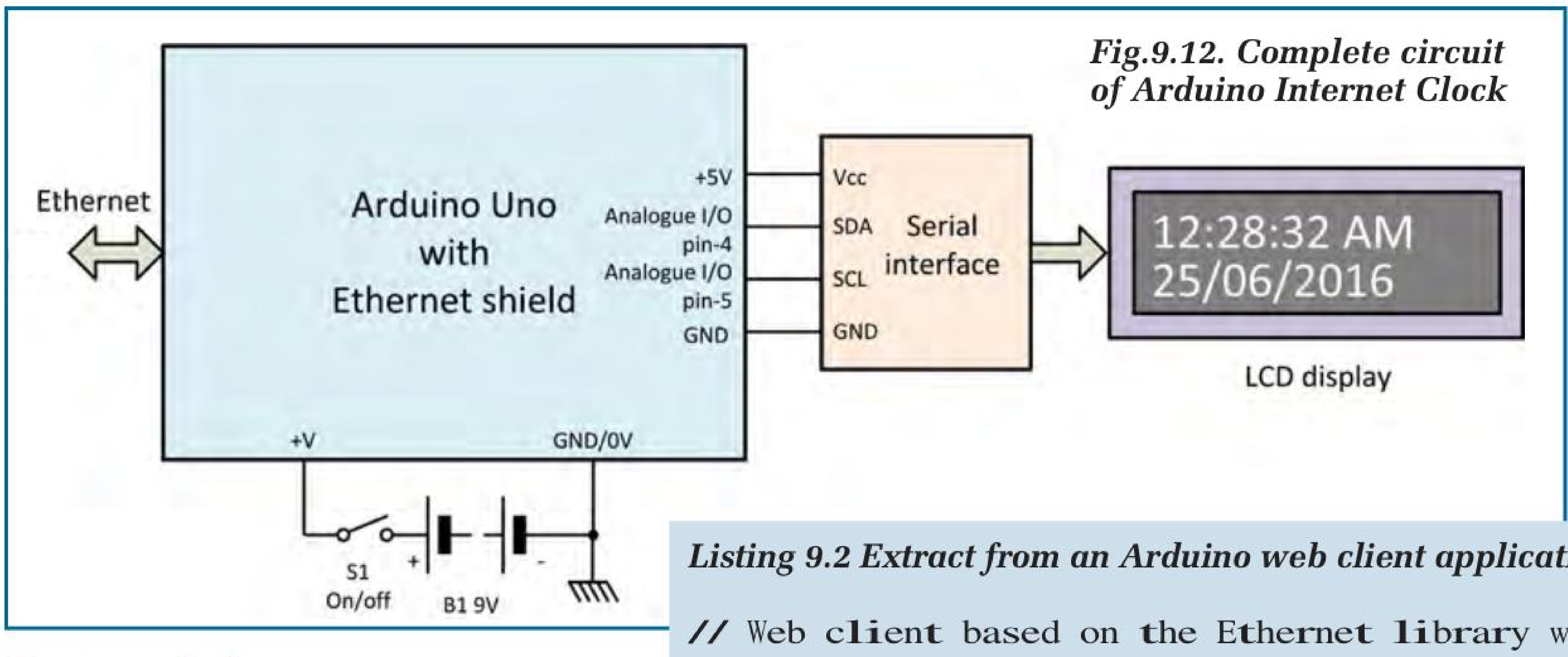


Fig.9.12. Complete circuit of Arduino Internet Clock

Testing and adjustment

When you've corrected any coding errors that the compiler reports you will be ready to upload your code to the Uno or Nano. Just click on the upload arrow and watch the progress report. After the Nano performs a reset and following a short delay you should find that the LCD shows the current GMT.

Going further

As always, there's a great deal of scope for going further with this month's *Get Real* project. For example:

- Adding one or more alarm functions using the unused digital I/O lines to sound a piezo buzzer, illuminate an LED, or even turn your lights on at dusk and off at dawn by using an external relay module.'
- Changing the display format to that commonly used in your own region (the code shown here displays in standard DD/MM/YYYY format, but some users might prefer something different)
- Providing an audible indication on the hour, half hour or quarter hour.

All of these additions could be easily incorporated into the basic Arduino Internet clock and they will provide you with a great opportunity to further develop your coding skills.

Next month

In next month's *Teach-In 2016, Arduino World* will look at ultrasonic sensors. *Arduino Workshop* will introduce you to the practical aspects of object proximity and distance sensing. Our programming feature, *Coding Quickstart*, investigates the ultrasonic library and our *Get Real* project will describe the design and construction of a proximity warning system based on the Arduino and a low-cost ultrasonic transmitter/receiver module.

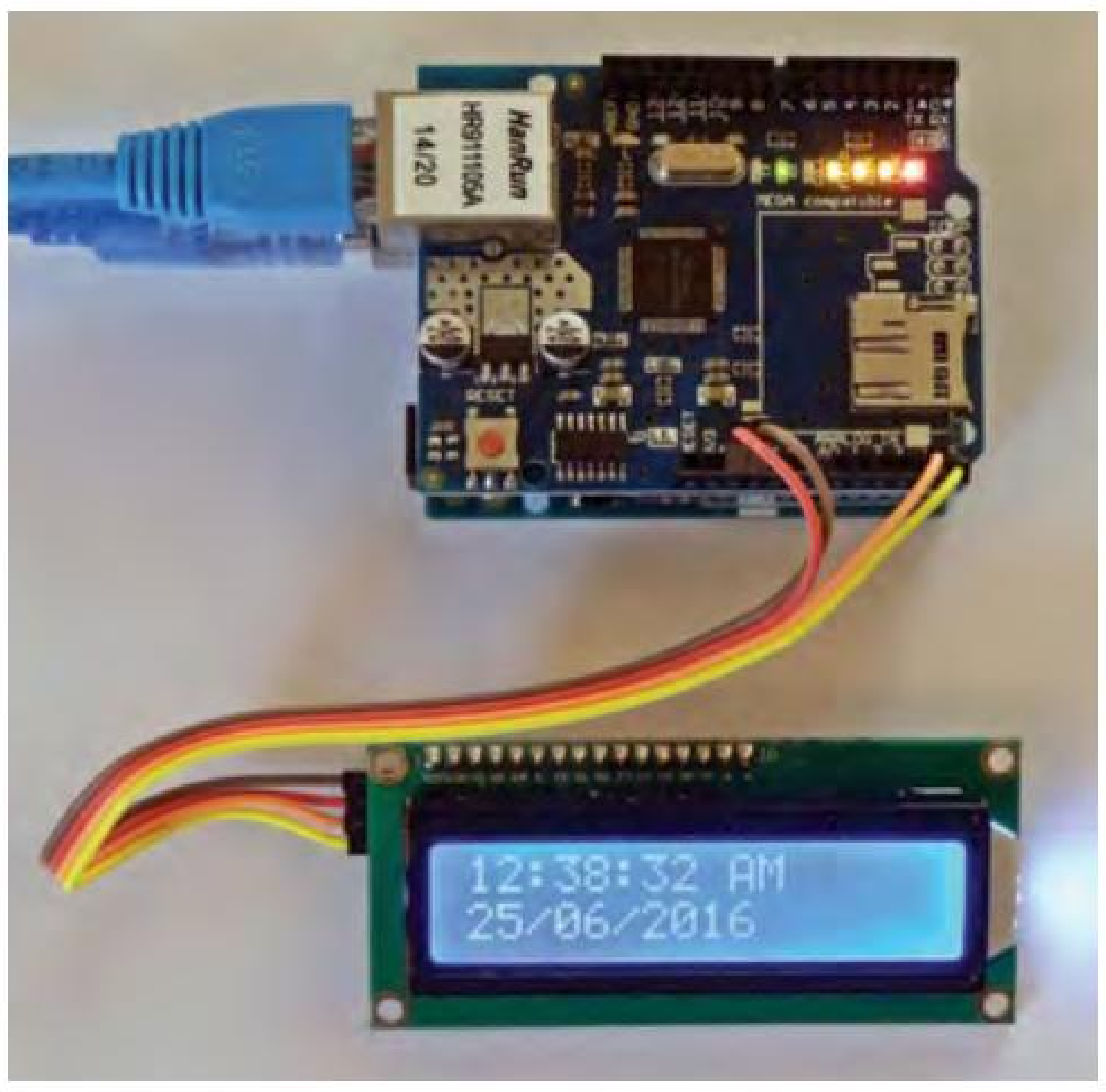
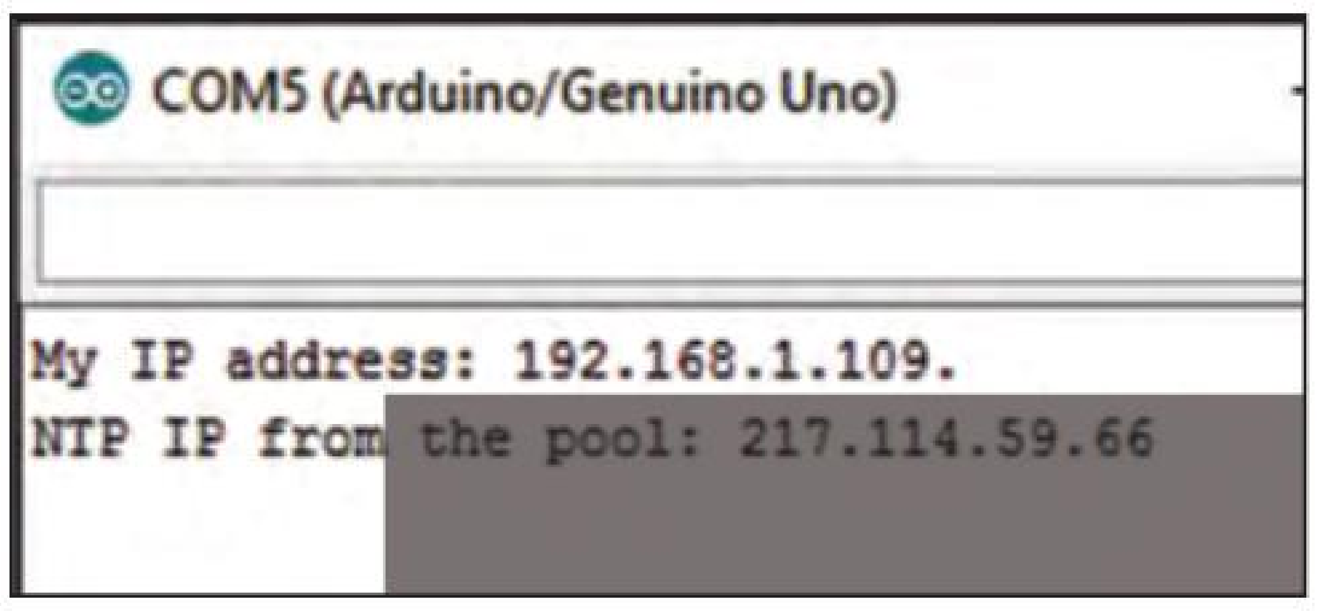


Fig.9.13. The complete Arduino Internet Clock

Listing 9.2 Extract from an Arduino web client application

```
// Web client based on the Ethernet library web client example

#include <SPI.h>
#include <Ethernet.h>

byte mac[] = { 0xDE, 0xAD, 0xBE, 0xEF, 0xFE, 0xED };

char server[] = "www.key2electronics.com"; // Web address using DNS

IPAddress ip(192, 168, 0, 177);  // Use static IP addressing

EthernetClient client;

void setup() {
  Serial.begin(9600);
  while (!Serial) {
  }

  // Start the Ethernet connection:
  if (Ethernet.begin(mac) == 0) {
    Serial.println("Failed to configure Ethernet using DHCP");
    // Try to configure using IP address instead of DHCP:
    Ethernet.begin(mac, ip);
  }
  // Wait for the Ethernet shield to initialize:
  delay(1000);
  Serial.println("Connecting...");

  // If you get a connection, report back via serial:
  if (client.connect(server, 80)) {
    Serial.println("connected");
    // Make a HTTP request:
    client.println("GET /atx.htm HTTP/1.0");
    client.println("Host: www.key2electronics.com");
    client.println();
  } else {
    // If you didn't get a connection to the server:
    Serial.println("Connection failed");
  }
}

void loop() {
  //If there are incoming bytes available
  // from the server, read them and print them:
  if (client.available()) {
    char c = client.read();
    Serial.print(c);
  }

  // Stop the client if the server is disconnected
  if (!client.connected()) {
    Serial.println();
    Serial.println("Disconnecting.");
    client.stop();

    // Do nothing
    while (true);
  }
}
```



```
COM5 (Arduino/Genuino Uno)

My IP address: 192.168.1.109.
NTP IP from the pool: 217.114.59.66
```

Fig.9.14. Using the time server allocation to obtain an NTP time server address

Listing 9.3 Extract from Arduino Internet Clock application

```
// Code originated at:
// http://www.openreefs.com/ntpServer
// Modified by Steve Spence,
// http://arduinotronics.blogspot.com
// Modified again by Mike Tooley for EPE

// *** Libraries to be included ***

#include <SPI.h>
#include <Ethernet.h>
#include <EthernetUdp.h>
#include <Time.h>
#include <Wire.h>
#include <LCD.h>
#include <LiquidCrystal_I2C.h>

// *** LCD display settings ***
// Set LCD display parameters but first add
// the address of your Ethernet shield. If
// necessary, you can use the Arduino's I2C
// Scanner application to find the address

#define I2C_ADDR 0x27 // <<----- 0x27 for this
                      // Ethernet shield
#define BACKLIGHT_PIN 3
#define En_pin 2
#define Rw_pin 1
#define Rs_pin 0
#define D4_pin 4
#define D5_pin 5
#define D6_pin 6
#define D7_pin 7

LiquidCrystal_I2C lcd(I2C_ADDR,En_pin,Rw_
pin,Rs_pin,D4_pin,D5_pin,D6_pin,D7_pin);

// *** Ethernet shield settings ***
// Set up AC address of your Ethernet shield
byte mac[] = { 0x90, 0xA2, 0xDA, 0x00, 0x23,
0x36 };

// *** Set up Network Time Protocol (NTP) ***
// You set this to your chosen time using
IPAddress timeServer(217, 114, 59, 66);

// *** Set offset (in seconds) to your local
// time. In this case we are using GMT so the
// offset is 60x60 = 3600 for UK summertime
const long timeZoneOffset = 3600;

// *** Synchronise to the NTP server ***
// Set this to 1 hour (3600 seconds) to reduce
// the load on the NTP server. For test
// purposes you'll probably need to change
// this to a shorter interval, say 15 seconds
unsigned int ntpSyncTime = 3600;

// *** NTP/UDP variables - ALTER VARIABLES AT
// YOUR OWN RISK ***
// local port to listen for UDP packets
unsigned int localPort = 8888;
// NTP time stamp is in the first 48 bytes of
// the message
const int NTP_PACKET_SIZE= 48;
// Buffer to hold incoming and outgoing packets
byte packetBuffer[NTP_PACKET_SIZE];
// A UDP instance to let us send and receive
// packets over UDP
EthernetUDP Udp;
// Keeps track of how long ago we updated the
// NTP server
unsigned long ntpLastUpdate = 0;
// Check last time clock displayed (Not in
// Production)
time_t prevDisplay = 0;

void setup() {
   lcd.begin (16,2);
   lcd.setBacklightPin(BACKLIGHT_
PIN,POSITIVE);
   lcd.setBacklight(HIGH);
   Serial.begin(9600);

// Ethernet shield and NTP setup
   int i = 0;
   int DHCP = 0;
   DHCP = Ethernet.begin(mac);
   // Try to get dhcp settings 30 times before
   // giving up
   while( DHCP == 0 && i < 30){
     delay(1000);
     DHCP = Ethernet.begin(mac);
     i++;
   }
   if(!DHCP){
    Serial.println("DHCP FAILED");
     for(;;); //Infinite loop because DHCP Failed
   }
   Serial.println("DHCP Success");

   //Try to get the date and time
   int trys=0;
   while(!getTimeAndDate() && trys<10) {
     trys++;
   }
}

// *** Now display the time and date in
// MM/DD/YY format ***

// Not shown in this extract but included in
// the full code that can be downloaded from
// www.epemag.com

// *** Finally, this is where all the magic
// happens ... ***
void loop() {
    // Update the time via NTP server
    if(now()-ntpLastUpdate > ntpSyncTime) {
      int trys=0;
      while(!getTimeAndDate() && trys<10){
        trys++;
      }
      if(trys<10){
       Serial.println("ntp server update success");
      }
      else{
       Serial.println("ntp server update failed");
      }
    }

    // Display the time if it has changed by
    // more than 1s
    if( now() != prevDisplay){
      prevDisplay = now();
      clockDisplay();
    }
}
```

CIRCUIT SURGERY

REGULAR CLINIC

BY IAN BELL

Phase-locked loops

CIRCUIT SURGERY topics are usually based on *EPE Chat Zone* discussions, but from time to time we also look at other topics which will help readers working on their own designs or working with technical documents from device manufactures. This month, we will look at the phase-locked loop (PLL), a topic suggested by *EPE* editor Matt Pulzer. PLLs have a wide variety of uses in electronic systems in both analogue and digital contexts, with FM demodulation and clock generation for microprocessors being respective examples.

A PLL produces an output signal that is locked to the timing (phase) of the input (reference) signal. In the simple case the PLL outputs the same frequency as the reference – this is useful, for example, in producing a sine wave at the same frequency as an input pulse train. However, the output does not have to be at the same frequency, if the output frequency is divided down (eg, using a digital counter) and the divided signal is locked to the reference, then the PLL output will be at a higher frequency, but locked to the reference by a multiplication factor.

PLLs have a reputation problem as 'difficult' circuits, only used in advanced radio systems and similar applications. It's probably true to say that designing a complete, high-performance PLL from scratch is not easy, but this is unnecessary for most people as suitable PLL chips or subsystems are available to use. Although their basic structure is quite straightforward, a vast number of academic papers and many textbooks have been published on their theory, design and use since their first implementation in the 1930s. This effort is driven by the fact that the performance of many advanced electronic systems depends on the performance of a PLL.

In-depth analysis of PLL characteristics and behaviour requires some advanced theory, but fortunately it is possible to make some useful circuits using PLL chips without needing to use difficult mathematics. Although, as always, getting to grips with the theory will be beneficial in more serious design work. In other contexts you may need to configure PLLs (eg, for the clock of a microcontroller) or decide if using a PLL is the best approach in a given design. In all cases some understanding of the basics of PLL operation and characteristics will be helpful.

Applications

PLLs have many applications in communications, including reconstruction of the carrier, demodulation of both AM (amplitude modulation) and FM (frequency modulation) signals, decoding FSK (frequency shift keying) signals, and receiver synchronisation for digital data transmission (including regenerating the clock from the data).

PLLs are also used in frequency synthesis – the production of accurate-frequency signals, often over a range of frequencies under digital control. In fact, this is probably their most well-known configuration, which itself has a variety of applications, including clock generation for digital circuits. In recent years direct digital synthesisers (DDS) have become an alternative to PLLs for frequency synthesis/signal generation in some contexts. Like a PLL, a DDS produces an output signal whose frequency is locked to an input reference, however its operating principle is different. The DDS provides advantages such as faster output frequency changes, better frequency resolution, and it is relatively easy to exactly synchronise multiple DDSs at difference phase offsets.

Many large digital ICs, such as processors, have PLLs as part of their clock system. The PLL can synchronise the internal clock with an external one, and allows the internal clock to be at a higher frequency than the external clock; furthermore, the phase shift of the PLL clock can be set to give good synchronisation between the timing of the chip's inputs and outputs.

One reason PLLs are used is that it is easier to produce and handle high frequency clocks (eg, hundreds of megahertz and upwards) on-chip than to generate if off-chip and transmit it across PCB tracks and chip pins into the chip. On the other hand, for the clock frequency to be accurate a crystal oscillator is required off-chip. The solution is to generate a relatively low frequency off-chip and multiply it up on-chip. On-chip PLLs also allow the system clock frequency to be varied along with core supply voltage – a common technique to manage power consumption (versus processing speed) in devices such as processors in mobile products.

Although we may think of a simple digital circuit as having a clock, that is a single clock, modern digital systems often require multiple clocks at different, and accurately controlled, frequencies. The frequencies are determined by the various interface and data standards, for example audio and video formats, graphical display standards, communications standards, memory chip timing requirements and ADC and DAC sample rates. On-chip PLLs can generate all the frequencies required for these various interfaces and formats from a single accurate-frequency external clock. Alternatively, where such clocks are required for various chips on a board, a PLL-based clock generator chip can be used.

Structure

The basic structure of a PLL is shown in Fig.1, where we can see that a PLL comprises a phase detector, a low-pass filter, an amplifier and a voltage-controlled oscillator (VCO). The frequency of oscillation of the VCO is determined by its control input voltage. The PLL is in fact a negative-feedback closed-loop control system, rather like a servomechanism that you might find in a radio control model. A 'demand' input (the position we require a servo motor to move to, or the frequency/phase for a PLL) is input and compared with the present output. An 'error signal' (the difference between the present and the demanded positions, or frequencies) is then used to move the output closer to the value we're demanding.

The phase detector compares the phase (and frequency) difference between its two input signals and produces an output dependent on (proportional to) this difference. The

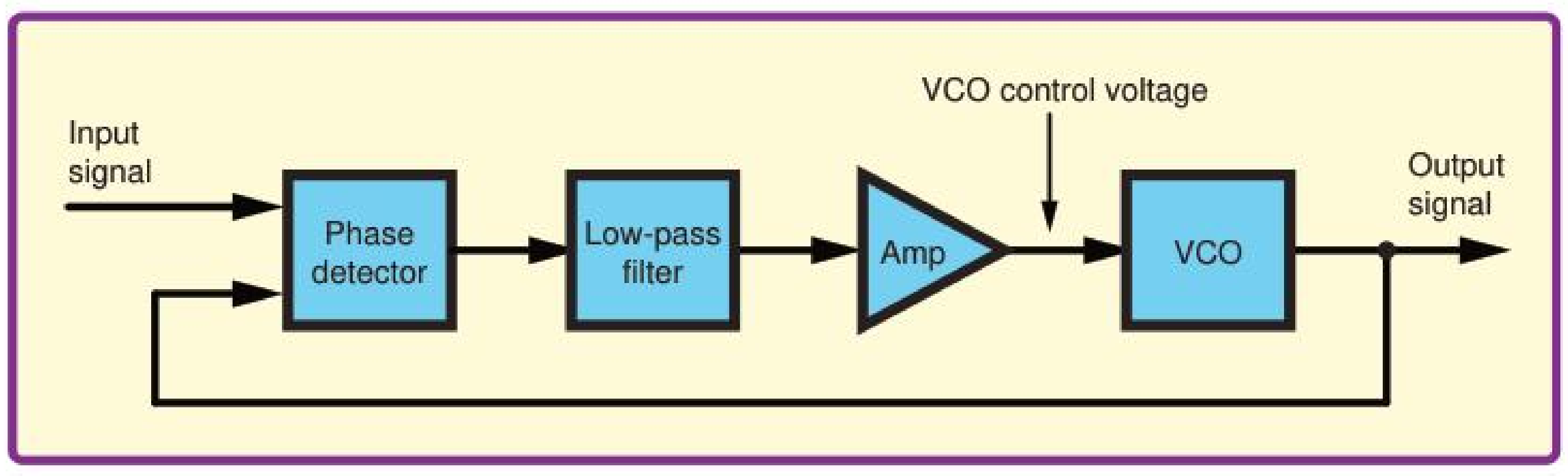


Fig.1. Basic PLL block diagram

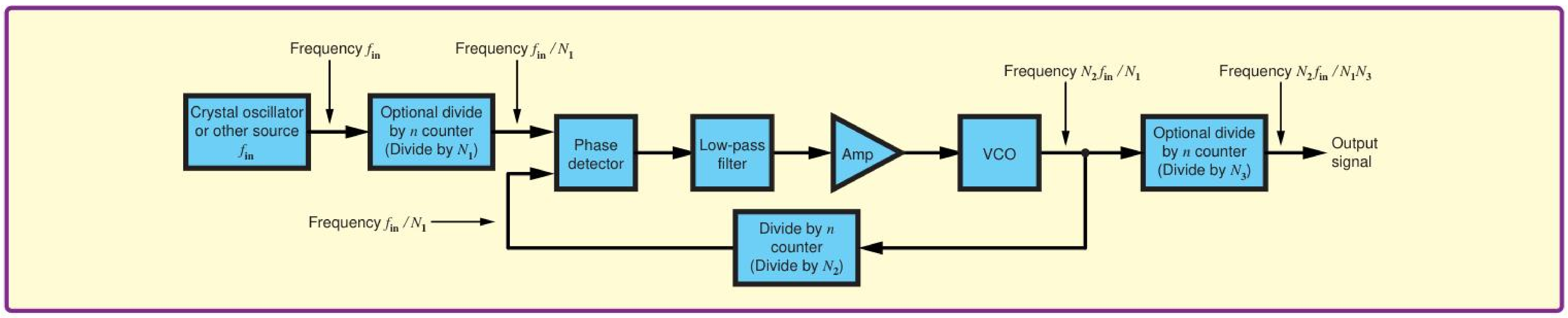

Frequency f_{in}
Frequency f_{in}/N_1
Frequency $N_2 f_{in}/N_1$
Frequency $N_2 f_{in}/N_1 N_3$
Crystal oscillator or other source f_{in}
Optional divide by n counter (Divide by N_1)
Phase detector
Low-pass filter
Amp
VCO
Optional divide by n counter (Divide by N_3)
Output signal
Frequency f_{in}/N_1
Divide by n counter (Divide by N_2)

Fig.2. PLL frequency synthesiser

phase detector output is smoothed by a low-pass filter (and buffered or scaled by the amplifier) to produce a control signal for the VCO. If there is a difference between the frequency (or phase) of the input signal and that of the VCO, then the signal from the phase detector and filter will cause the VCO control voltage to change, such that the VCO frequency is moved closer to the input frequency.

Eventually, the two frequencies will become equal and attain a fixed phase relationship, at which point the PLL is described as being 'locked'. The process of 'homing in' on the input frequency is called capture, acquisition, or pull-in. Once locked, the PLL can track changes in the input frequency (remaining locked) as long as these changes are not too large or fast. Important parameters that measure PLL performance are:

- Capture time (how fast it locks onto a frequency)
- Lock range (what range of frequencies it will stay locked to, once locked)
- Capture range (the range of frequencies it will capture, starting in the non-locked state).

Other important PLL specifications relate to noise and stability, including the response of the PLL to noise on its input, the noise on its output, and the stability of the output signal's phase and frequency (characterised in terms of output phase noise). For different applications these specifications may take on a different significance. For example, a small capture range will be useful for some tasks but not others. A large capture range makes the PLL more susceptible to noise, whereas a small capture range makes capture more difficult to achieve. It's possible to switch the properties of the filter after lock is obtained to get the best overall performance. The ability of the PLL to 'lock' to noisy input signals is key to its usefulness in communications systems where high levels of noise may be present.

A PLL may have additional outputs to the signal output shown in Fig.1. For example, a 'locked' signal to indicate if the PLL is locked, or an output obtained from the VCO control voltage proportional to the frequency. In general, VCO and phase detector outputs may be used for decoding/demodulation purposes. One example of using a locked indication is where a digital system requires an accurate clock for given interface/data standard – the system/processor should wait until lock is obtained before using the interface.

The way in which a PLL attains lock is complex – the VCO control signal during capture (ie, when the PLL is not locked) is not a simple DC representation of the difference in frequencies between the two signals. However, in simple terms, the DC component, or average value, over time, of the VCO control signal moves towards the value required to lock the PLL.

Frequency synthesisers

Fig.2 shows a simple block diagram of a PLL-based frequency synthesiser capable of producing a wide range of frequencies using a single fixed crystal-controlled oscillator or other reference source. The frequency can be digitally programmable – ie, it could be set by a set of switches, additional logic circuitry or a microcontroller. The circuit is a basic PLL (Fig.1) with from one to three (potentially programmable) divide-by-N counters added.

The counters are sequential logic circuits that divide an input frequency by N. The value of N may be fixed, be entirely programmable or, where the input frequency is high (making a programmable counter design more challenging), the counter may comprise a fast non-programmable counter/divider called a prescaler followed by the programmable stage. The value of N may be set directly by a binary number input (so all possible values can be used) or the input may select from a set of division values.

The first counter (in Fig.2) is optional and divides the crystal oscillator (or other input) frequency f_{in} by the integer value N_1 to give the reference input to which the PLL will lock. Thus the PLL will lock onto f_{in}/N_1. The second counter divides the VCO output, so that the phase detector is comparing the input with a divided version of the VCO frequency. The PLL will lock when the divided VCO frequency matches the input frequency – so the VCO will be running at N_2 times the input frequency, ie, $N_2 f_{in}/N_1$ (or simply $N_2 f_{in}$ if the first counter is not present). The PLL is acting as a frequency multiplier. The output from the frequency synthesiser is the PLL's VCO output, or a division of that frequency (ie, $N_2 f_{in}/N_1 N_3$ or $N_2 f_{in}/N_3$) if the third (optional) counter on the output is used.

The VCO can have any wave shape (sine, square, triangular etc) and by selection of N_1, N_2 and N_3 a range of possible frequencies can be produced. Although all three counter/dividers are not always required, together they tend to provide the best performance. Which configuration is best depends on the impact on PLL/synthesiser performance in relation to the application's requirements. For example, if the input frequency to the phase detector is low (more likely with large N_1) then locking is more likely to be slow (and has other problems with signal quality). On the other hand, a lower input frequency to the phase detector means that the frequency resolution is better – the difference between the frequencies the synthesiser can produce (as N_2 is varied) is smaller (often an important characteristic). Using an output (N_3) divider overcomes problems with low input frequency to the phase detector, but may be problematical because the VCO has to run at relatively high frequencies. Using both the input and output dividers provides a compromise between these issues.

The PLL-based frequency synthesisers described so far have integer dividers (N_1, N_2 and N_3 are all integers) and are therefore referred to as integer-N synthesisers or PLLs. The combination of multiplication and division means that the output frequency can be a fractional (non-integer) multiple of the input (eg, $N_2 f_{in}/N_1$), which is needed for good frequency resolution, but this requires use of the input and/or output dividers with the problems just discussed. An alternative approach is for N_2 to be directly non-integer, which is referred to as a fractional-N synthesiser or PLL. Dividing an input frequency by a non-integer amount using a digital circuit is much more complex than using a standard counter circuit to divide by an integer. It can be achieved by switching between two (or more) different integer divisions so that the average division is the required value. Signal quality may not be as good as with integer-N PLLs due to the constantly changing phase detector input caused by switching the dividers. Input and output dividers can still be used with a fractional-N PLL, but do not need to have such large values.

The 4046

The most popular general-purpose analogue PLL chip is the 4046. It has been around for a long time and is available from various manufacturers

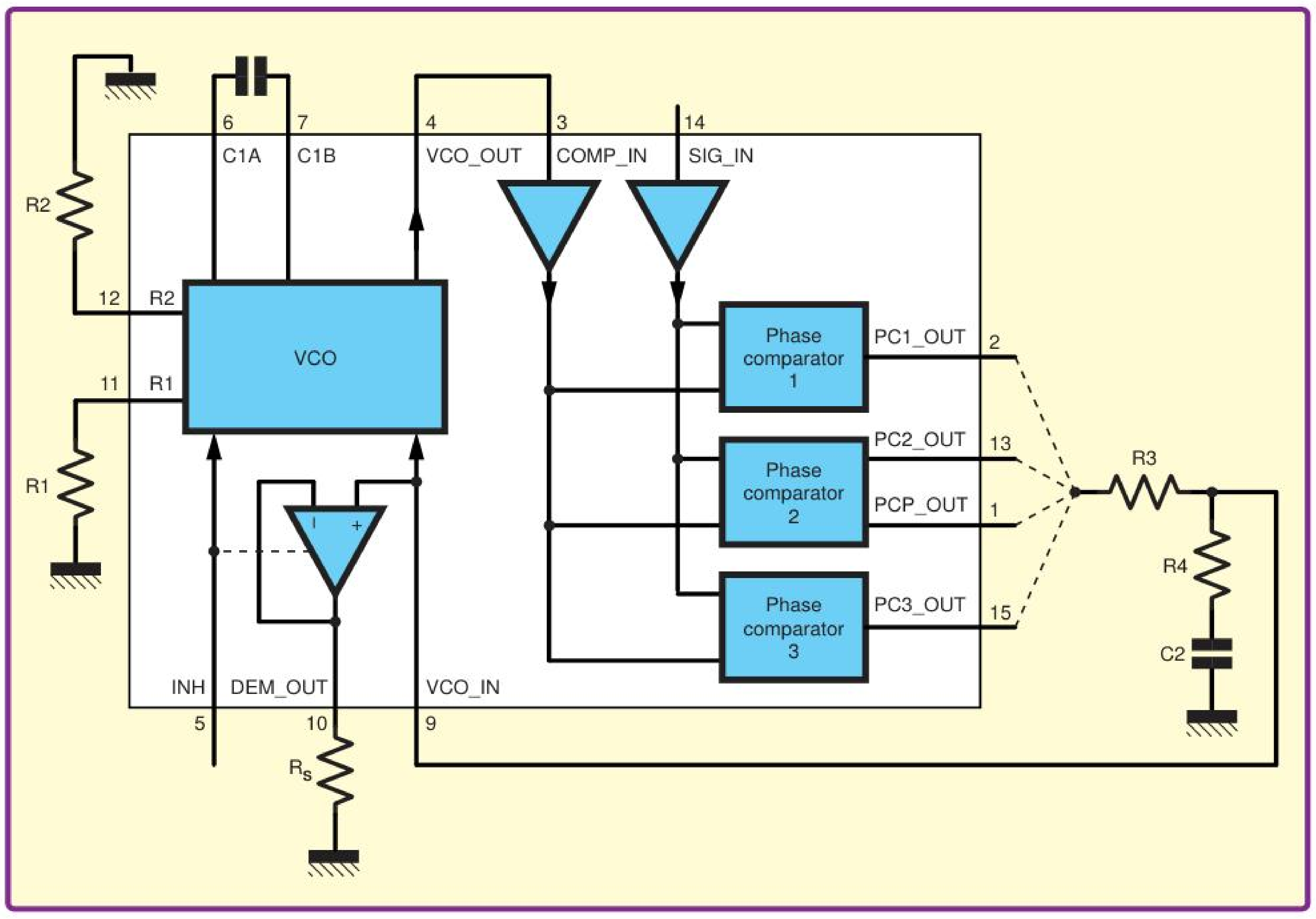

6
C1A
7
C1B
4
VCO_OUT
3
COMP_IN
14
SIG_IN
R2
12
R2
VCO
11
R1
R1
Phase comparator 1
PC1_OUT
2
Phase comparator 2
PC2_OUT
13
PCP_OUT
1
R3
R4
Phase comparator 3
PC3_OUT
15
C2
INH
DEM_OUT
VCO_IN
5
10
9
R$_S$

Fig.4. Internal block diagram and basic external components for the 74HC4046A/74HCT4046A (from NXP Datasheet, 2016)

(eg, Texas Instruments and NXP) and in a variety of forms, with slightly different features. The 4046 can be used for analogue PLL applications such as demodulation and can be used together with programmable counter ICs, such as the 4059, to build frequency synthesisers. Because of its longevity and popularity there are plenty of example circuits available for experimenters to try out.

In terms of variants, the HEF4046B has two different phase detectors, whereas the 74HCT4046A has three. The 74HCT9046A has a bandgap-controlled VCO, which is more stable with variations in supply voltage and temperature than other versions. The CD74HCT7046A has two phase comparators and a lock detector output to indicate when the PLL is locked. Different versions have different maximum frequencies. For example, the CD4046B can work up to 1.4MHz, whereas the CD74HCT4046A can go to 18MHz. All this means you need to take care when selecting which chip you purchase. The pin-out of the 74HC/HCT4046A is shown in Fig.3, and Fig.4 shows an internal block diagram and the connection of the key external components required in even the most basic 4046-based PLL.

The 4046 contains two or three phase comparators to choose from; however, the low-pass filter is made using external components (R3, R4 and C2 in Fig.4). Pin 10 (DEM$_{OUT}$) provides a buffered version of the low-pass filter output (and VCO input) so that this signal appears as the voltage across R$_S$ and can be used elsewhere in your circuit without loading the filter. To use the PLL you need to decide on the lock-range frequencies (which determine the VCO frequencies and hence C1, R1 and R2), the low-pass filter values (R3 and C2), and which phase comparator to use. None of this is trivial, however manufacturers provide data sheets and/or application notes which provide data and procedures for calculating component values – for example, graphs to show how the VCO centre frequency is set by the values of C1, R1 and R2.

The two phase comparators operate on different principles and have different characteristics, benefits and potential problems. Phase comparator 1 is simply an XOR gate. When using phase comparator 1 the signal and reference inputs must both have 50% duty cycle in order to achieve maximum lock range. Phase comparator 2 is more complicated than phase comparator 1. It is a state machine which changes state when logic transitions occur on either the signal or reference inputs. Phase comparator 2 also has another output PCP$_{out}$ (phase comparator pulse output) on pin 1 that can be used to tell when the PLL is locked. Phase comparator 3 is a positive edge-triggered sequential phase detector using an RS-type flip-flop. When the PLL is using this comparator, the loop is controlled by positive signal transitions.

The loop filter should use the longest RC time possible for the application. This depends on the speed with which the input frequency changes. If the RC time constant of the loop filter is too long the PLL will not move fast enough to track changes. If it is too short the VCO frequency will jump around too much, in the worst case responding to individual cycles of the input signal. The performance of the PLL can be improved by using a resistor in series with C2 (R4 in Fig.4). This produces damping in the loop filter and makes the PLL more stable. A typical value for this resistor is about a tenth of the value of R3.

Clock generators

The 4046 is useful for a variety of PLL circuits, but as indicated above, PLLs are encountered in other contexts such as processor clocks. An example of this is shown in Fig.5, which is part of the clock system for the PIC18F87J50 family device from Microchip. Either the external or internal osciallator can be routed to provide the input to the 96MHz PLL, with various prescaling options. The output of the PLL (divided to 48MHz) can be used as the primary system clock if wanted

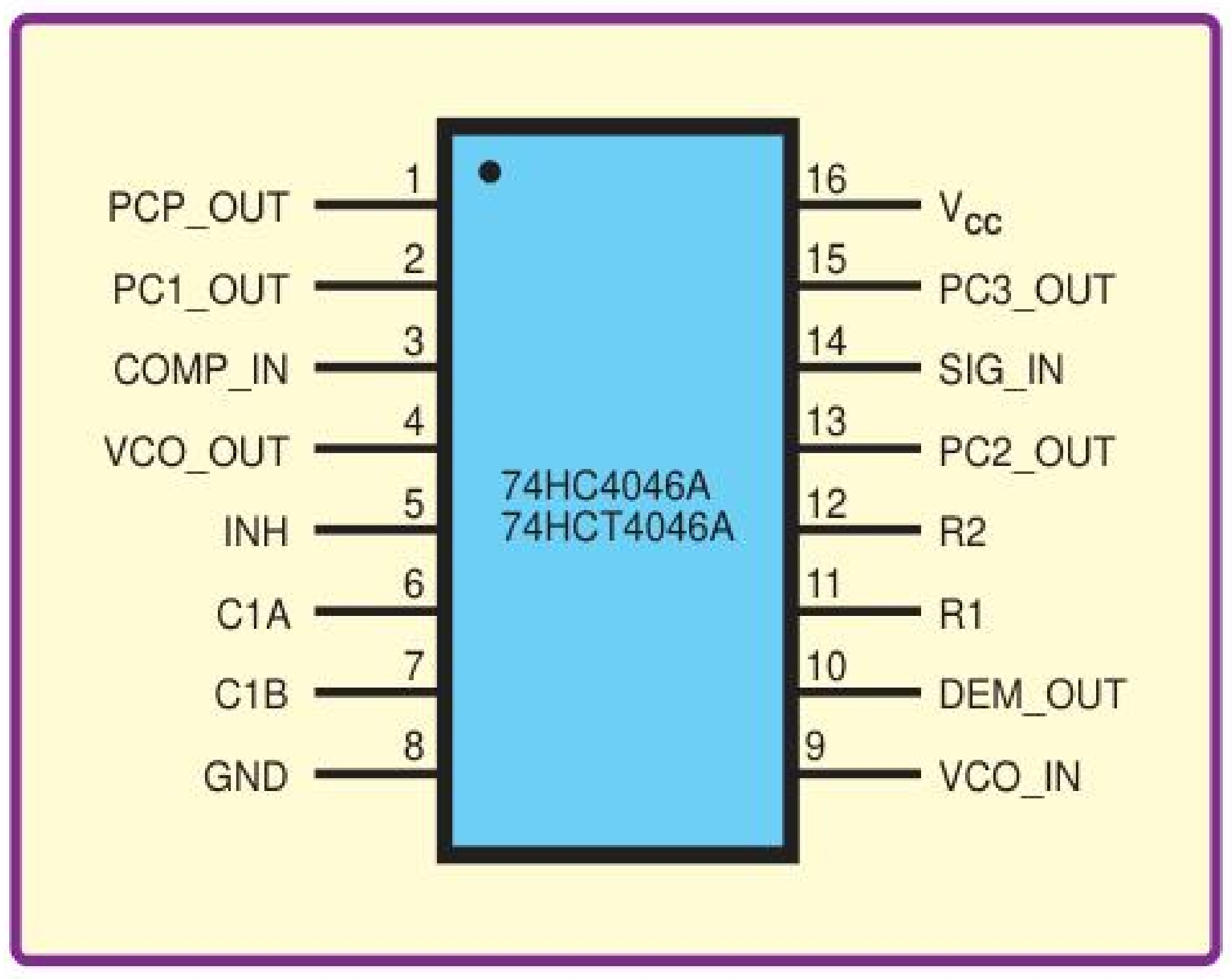

PCP_OUT
1
PC1_OUT
2
COMP_IN
3
VCO_OUT
4
INH
5
C1A
6
C1B
7
GND
8
16
V$_{CC}$
15
PC3_OUT
14
SIG_IN
13
PC2_OUT
12
R2
11
R1
10
DEM_OUT
9
VCO_IN
74HC4046A
74HCT4046A

Fig.3. 74HC4046A/74HCT4046A pin connections (from NXP Datasheet, 2016)

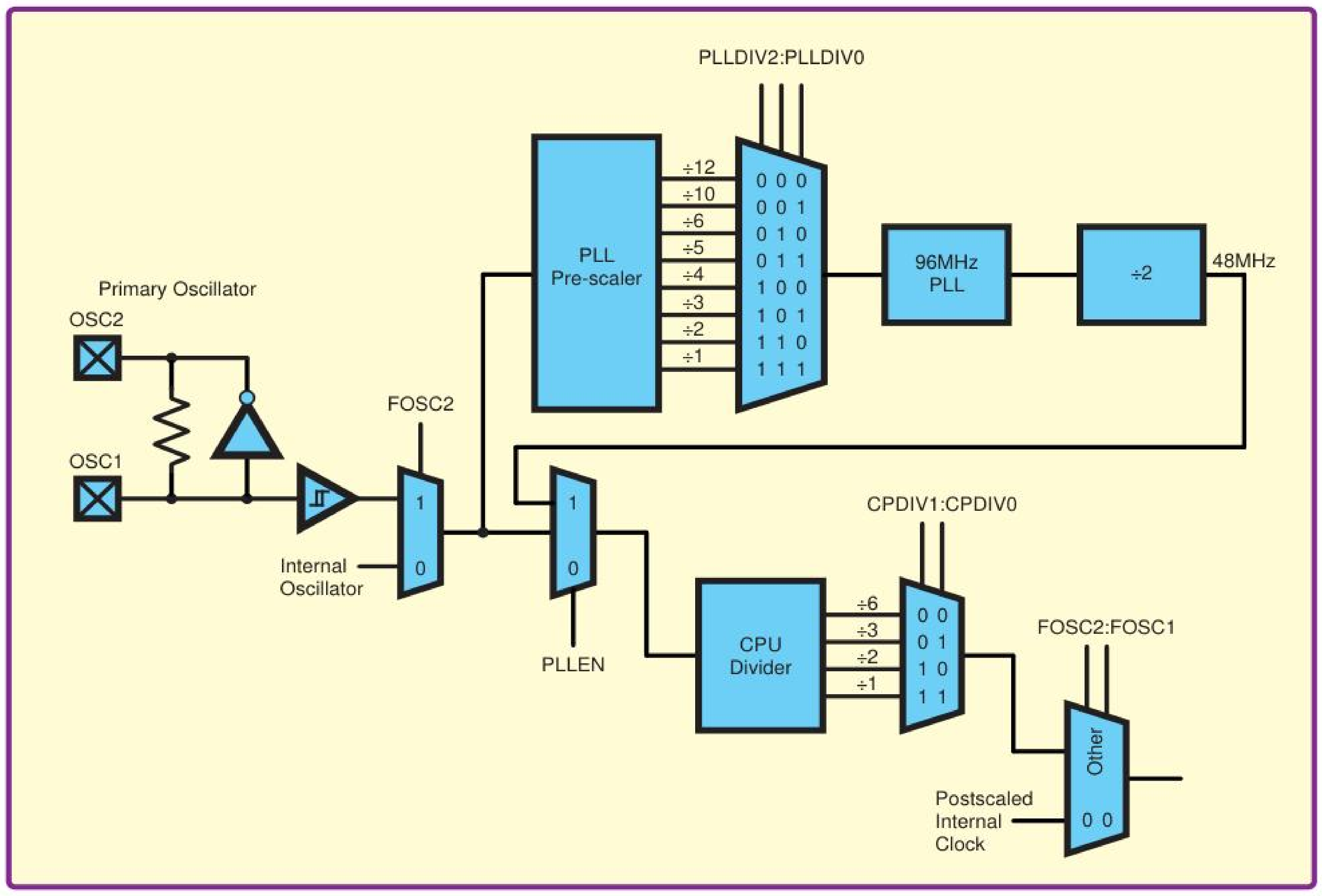

PLLDIV2:PLLDIV0
PLL Pre-scaler
÷12
÷10
÷6
÷5
÷4
÷3
÷2
÷1
0 0 0
0 0 1
0 1 0
0 1 1
1 0 0
1 0 1
1 1 0
1 1 1
96MHz PLL
÷2
48MHz
Primary Oscillator
OSC2
OSC1
FOSC2
1
0
Internal Oscillator
1
0
PLLEN
CPDIV1:CPDIV0
CPU Divider
÷6
÷3
÷2
÷1
0 0
0 1
1 0
1 1
FOSC2:FOSC1
Other
0 0
Postscaled Internal Clock

Fig.5. Example use of a PLL in a microcontroller clock system (based on PIC18F87J50 family data sheet)

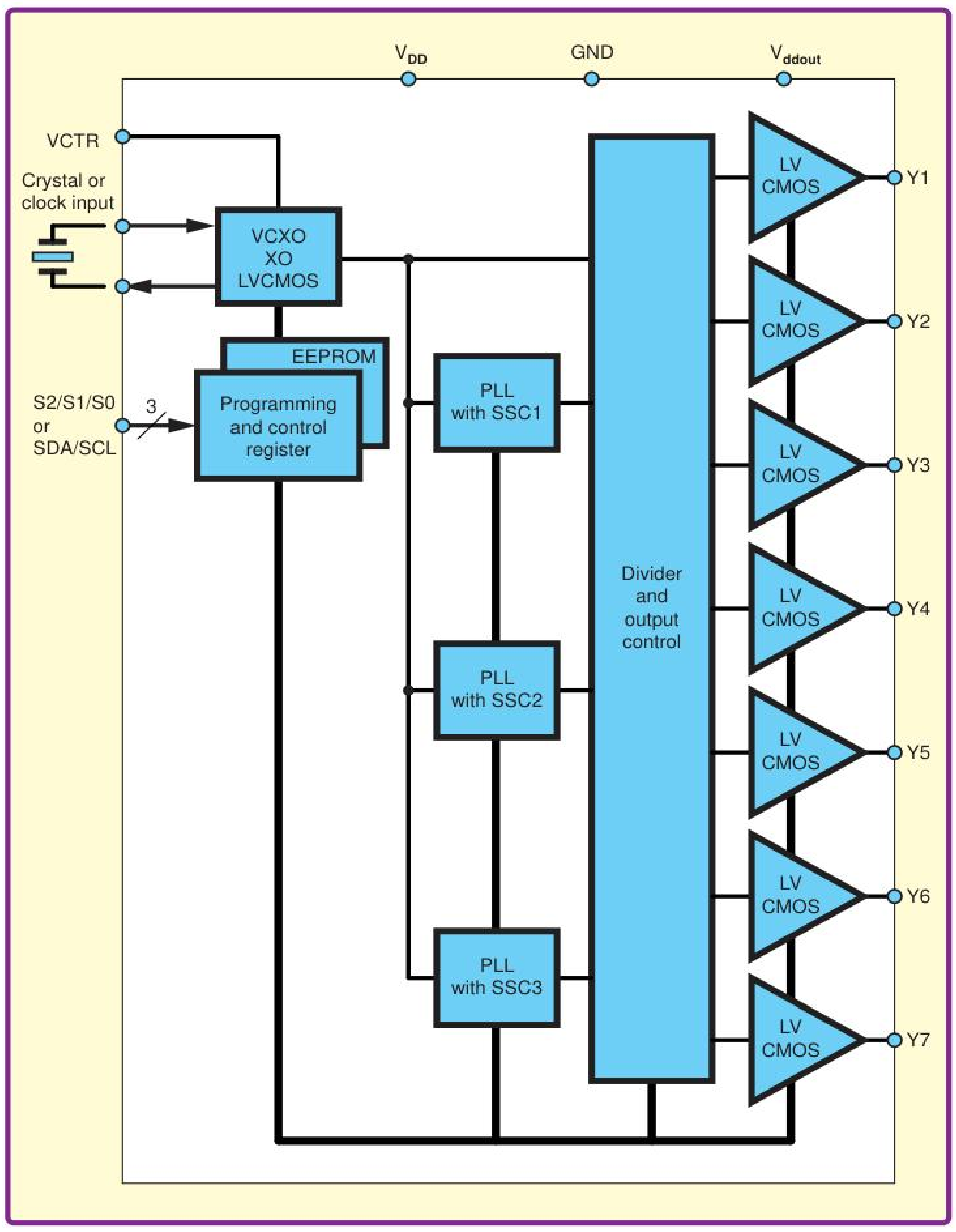


Fig.6. Example PLL-based clock generator IC block diagram. This is the CDCE937 from Texas Instruments

and can be further divided if required. The various clocking options are set up by writing to control/configuration registers on the device.

Another example of PLL-based clocking is shown in Fig.6. This is a block diagram of the CDCE937 Programmable 3-PLL VCXO Clock Synthesizer IC from Texas Intsruments. Chips like this can be used on digital system boards where various devices need different clock inputs, The CDCE937 can generate up to seven output clocks from a single reference frequency provided by the on-chip voltage-controlled crystal oscillator (VCXO). It can generated clock frequencies up to 230MHz using its three independent PLLs. Each output can be programmed in-system via serial interface with the configuration stored in on-chip non-volatile EEPROM. The PLLs can provide spread-spectrum clocking (SSC) where the clock frequency is varied so that the circuit does not emit strong interference at one frequency (the peak emission is smaller).

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HP 54600B Oscilloscope Analogue/Digital Dual Trace 100MHZ

MARCONI 2955B Radio Communications Test Set

FLUKE/PHILIPS PM3092 Oscilloscope 2+2 Channel 200MHZ Delay TB, Autoset etc

LAMBDA GENESYS	PSU GEN100-15 100V 15A Boxed As New	£325
LAMBDA GENESYS	PSU GEN50-30 50V 30A	£325
HP34401A	Digital Multimeter 6.5 digit	£275-£325
HP33120A	Function Generator 100 microHZ-15MHZ	£260-£300
HP53131A	Universal Counter 3GHZ Boxed unused	£500
HP53131A	Universal Counter 225MHZ	£350
HP54600B	Digital Oscilloscope 100MHZ 20MS/S	from £75
IFR 2025	Signal Generator 9kHz - 2.51GHZ Opt 04/11	£900
Marconi 2955B	Radio Communications Test Set	£800
R&S APN62	Syn Function Generator 1HZ-260KHZ	£195
Fluke/Philips PM3092	Oscilloscope 2+2 Channel 200MHZ Delay etc	£250
HP3325A	Synthesised Function Generator	£195
HP3561A	Dynamic Signal Analyser	£650
HP6032A	PSU 0-60V 0-50A 1000W	£750
HP6622A	PSU 0-20V 4A Twice or 0-50V 2A Twice	£350
HP6624A	PSU 4 Outputs	£350
HP6632B	PSU 0-20V 0-5A	£195
HP6644A	PSU 0-60V 3.5A	£400
HP6654A	PSU 0-60V 0-9A	£500
HP8341A	Synthesised Sweep Generator 10MHZ-20GHZ	£2,000
HP83731A	Synthesised Signal Generator 1-20GHZ	£1,800
HP8484A	Power Sensor 0.01-18GHZ 3nW-10uW	£75
HP8560A	Spectrum Analyser Synthesised 50HZ - 2.9GHZ	£1,250
HP8560E	Spectrum Analyser Synthesised 30HZ - 2.9GHZ	£1,750
HP8563A	Spectrum Analyser Synthesised 9KHZ-22GHZ	£2,250
HP8566B	Spectrum Analsyer 100HZ-22GHZ	£1,200
HP8662A	RF Generator 10KHZ - 1280MHZ	£750
Marconi 2022E	Synthesised AM/FM Signal Generator 10KHZ-1.01GHZ	£325
Marconi 2024	Synthesised Signal Generator 9KHZ-2.4GHZ	£800
Marconi 2030	Synthesised Signal Generator 10KHZ-1.35GHZ	£750
Marconi 2305	Modulation Meter	£250
Marconi 2440	Counter 20GHZ	£295
Marconi 2945	Communications Test Set Various Options	£2,500
Marconi 2955	Radio Communications Test Set	£595
Marconi 2955A	Radio Communications Test Set	£725
Marconi 6200	Microwave Test Set	£1,500
Marconi 6200A	Microwave Test Set 10MHZ-20GHZ	£1,950
Marconi 6200B	Microwave Test Set	£2,300
Marconi 6960B with	6910 Power Meter	£295
Tektronix TDS3012	Oscilloscope 2 Channel 100MHZ 1.25GS/S	£450
Tektronix 2430A	Oscilloscope Dual Trace 150MHZ 100MS/S	£350
Tektronix 2465B	Oscilloscope 4 Channel 400MHZ	£600
Cirrus CL254	Sound Level Meter with Calibrator	£40
Farnell AP60/50	PSU 0-60V 0-50A 1KW Switch Mode	£195
Farnell H60/50	PSU 0-60V 0-50A	£500
Farnell B30/10	PSU 30V 10A Variable No Meters	£45
Farnell B30/20	PSU 30V 20A Variable No Meters	£75
Farnell XA35/2T	PSU 0-35V 0-2A Twice Digital	£75
Farnell LF1	Sine/sq Oscillator 10HZ-1MHZ	£45
Racal 1991	Counter/Timer 160MHZ 9 Digit	£150
Racal 2101	Counter 20GHZ LED	£295
Racal 9300	True RMS Millivoltmeter 5HZ-20MHZ etc	£45
Racal 9300B	As 9300	£75
Black Star Orion	Colour Bar Generator RGB & Video	£30
Black Star 1325	Counter Timer 1.3GHZ	£60
Ferrograph RTS2	Test Set	£50
Fluke 97	Scopemeter 2 Channel 50MHZ 25MS/S	£75
Fluke 99B	Scopemeter 2 Channel 100MHZ 5GS/S	£125
Gigatronics 7100	Synthesised Signal Generator 10MHZ-20GHZ	£1,950
Panasonic VP7705A	Wow & Flutter Meter	£60
Panasonic VP8401B	TV Signal Generator Multi Outputs	£75
Pendulum CNT90	Timer Counter Analyser 20GHZ	£750
Seaward Nova	PAT Tester	£95
Solartron 7150	6 1/2 Digit DMM True RMS IEEE	£65
Solartron 7150 Plus	as 7150 plus Temp Measurement	£75
Solatron 7075	DMM 7 1/2 Digit	£60
Solatron 1253	Gain Phase Analyser 1mHZ-20KHZ	£600
Tasakago TM035-2	PSU 0-35V 0-2A 2 Meters	£30
Thurlby PL320QMD	PSU 0-30V 0-2A Twice	£160-£200
Thurlby TG210	Function Generator 0.002-2MHZ TTL etc Kenwood Badged	£65

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NET WORK

by Alan Winstanley

A security reminder

I HOPE readers enjoyed the last two *Net Work* columns that charted the evolution of the 'net over the past fifty years. Many life-enhancing benefits will doubtless emerge as Internet technologies continue to develop. Unfortunately, criminals are constantly seeking new ways of attacking victims by exploiting a network system's 'back door'. After all, history reminds us how the Maginot Line, the super-elaborate and heavily reinforced defence line built by the French before WWII proved of little use because the German army simply went round it. (See **www.lignemaginot.com** for the history.)

Fraudsters can infiltrate a home network by posting adverts on popular (or seedy) web pages that link through to bogus websites, where personal data can be harvested or ransomware introduced onto the victim's system. Flash-based ads can be highly insecure, which is why Flash is increasingly disabled in web browsers. Victims can be steered towards bogus copies of banking or finance websites, where logins can be stolen. To avoid DNS hijacking, change the default logins of your router and NAS, and confirm that the DNS server addresses of your Internet connection are as expected: your ISP can advise what they should be. Innocent-looking Microsoft Word and Excel documents can contain macros that introduce a virus, so macros should be turned off by default (see Word Options/ Trust Center Settings). Avoid untrusted file and driver download websites as much as possible, and steer well clear of bogus websites that offer free PDFs of books or magazines, because that is a perfect opportunity to 'hook' a greedy user who's hungry to download something for nothing. Suspicious file attachments, especially .zip, Office, .rtf, .scr or PDF files, can carry malware and wreak total havoc on an unguarded home or office network.

Personal data continues to leak out of insecure web-based systems as a matter of course: SanrioTown is the *Hello Kitty* community website where 3.3 million user details were stolen at the end of 2015. Earlier, toy-maker VTech had a data breach at its Learning Lodge website that yielded some 11.7 million parents' and kids' user profiles. It was claimed that no credit card details were stolen, and in December a British hacker was arrested for this crime.

One way of helping to safeguard one's data is to use robust, differing passwords for critical 'regular use' websites such as Facebook, eBay and Twitter, and use a different 'rubbish' login and throwaway email address for 'don't care' websites such as newspaper forums where it doesn't matter if your details are stolen. GMX offers free email addresses, for example, or you could try setting up a separate Gmail address. Obviously, never use the same password everywhere, but it's also wise to add a symbol such as an equal sign or hash at the start or end of a password to make dictionary attacks more difficult. The scale of website hacks is now almost too large to comprehend: hundreds of millions of user details were stolen from Adobe and LinkedIn over several years, and you can enter your email address at **https://haveibeenpwned.com** to see whether yours was one of them. You might want to change your logins as a result, or close the account altogether.

Roboform is an encrypted password management program that I find indispensable on my Windows PC for handling logins (also Mac and Android), but I still will not use any cloud-based password service no matter what assurances about security are offered. Roboform is also great for remembering tiresome and complicated web forms, and you can try the free version that allows ten 'passcards': handy for websites you use frequently.

The one that got away

Blind reliance upon online services can sometimes produce lighter moments. Recently, I was strolling through a busy market town when a motorist pulled up alongside me, asking for directions to the local fishing tackle shop. He brandished his smartphone, hooked it to a wireless hotspot and proudly showed an online map with directions to the store in question. We were barely 50m away from it according to the map, but the shop was nowhere to be seen. In fact, the entire block had been bulldozed several years ago and was now a housing complex. The online map was out of date and sadly the keen fisherman had wasted his journey. It did highlight how users seem to have an unswerving faith in some online services though.

The same could be said of the current Pokémon Go craze, the monster-searching game that's got players around the world glued to their smartphone screens. It is the creation of John Hanke, better known for creating Google Earth. The developer Niantic raised $20 million from Nintendo, Google and The Pokémon Co to produce a real-time augmented reality game in which geo-location techniques are used to superimpose Pokémon creatures onto smartphone camera shots in real time. All you have to do is wander around and 'catch them'. The sight of mobile phone users walking down the street while clicking their phones is common enough, but Pokémon Go has taken this to a new level. It's reported that several teenage girls were blindly following their screens late at night and it led them to walk directly towards the sea in search of more monsters. The lifeboat had to be called to avert a tragedy, and fans of the game have been warned not to walk into the sea! Four teenagers got lost in an English cave while hunting Pokémon, reportedly needing rescuing by three fire crews, and the LA Times reports that two men fell off a cliff while seeking the fabled monsters. The game contains 'numerous significant risks' as one school report put it, and youngsters are having to be trained into watching where they are going and being aware of their surroundings.

That's all for this month's *Net Work*. You can contact the author at **alan@epemag.demon.co.uk** or send comments for possible inclusion in *Readout* to **editorial@wimborne.co.uk**

PIC n' Mix

Mike O'Keeffe

Our periodic column for PIC programming enlightenment

PICs and the PICkit 3: A beginner's guide – Part 5

THIS MONTH we reach Part 5 of our beginner's guide, and we're going to move a little faster and work on Lesson 3 and Lesson 4 from the *PICkit 3 Starter Kit User's Guide*. Lesson 3 builds on last month's code, and instead of blinking just one of the Demo Board's LEDs, we will rotate lighting all four of them. In Lesson 4 we move on from the binary world of blinking lights and look at ADCs (analogue-to-digital converters). ADCs let PICs talk to the 'real world' of varying quantities and are therefore a common function of microcontrollers and a big subject in themselves. We could spend months talking about the inner workings of ADCs (even the maths can be quite daunting), but this is a PIC column, so I'll keep it light, interesting and educational.

You will gain a greater insight into PICs and what we're trying to achieve if you read the previous articles in this series. You will also need the following software and hardware:

1. Purchase the PICkit 3 Low Pin Count Demo Board (**http://tinyurl.com/h2jj2ek**)
2. Purchase the PICkit 3 Programmer + USB Cable (**http://tinyurl.com/zcpx3le**)
3. Download *PICkit 3 Starter Kit User's Guide* (**http://tinyurl.com/jyqfeuk**)
4. Download MPLAB X IDE (**http://tinyurl.com/hmehqja**)
5. Download XC8 Compiler (**http://tinyurl.com/h5g9k5l**)

Code

Before we proceed, a couple of general points about code. First, all of the C and assembly code mentioned in this series can be downloaded from the following link: **http://tinyurl.com/z2dm5k3**. I deliberately avoided mentioning this in previous articles because it is genuinely beneficial to type in your own code, make mistakes and learn to troubleshoot errors. However, as the code size increase, correcting errors can become frustrating and it becomes difficult to fit all the code into the limited space of an article. So, feel free to download and use the code, but do also get some practice in writing your own.

Second, I mentioned previously that all the Lessons can be written in assembly code as an alternative to C. Assembly is not the easiest of languages to start off with, and some beginners find it so frustrating that they are put off progressing. That said, assembly is powerful and useful, so if you are feeling adventurous then do examine the code in the link mentioned above.

Lesson 3 – rotate LEDs

We blinked one LED in the previous lesson, but what about the other LEDs? We could simply turn them all on, but let's try something more interesting – and a little more difficult. Lesson 3 can be found on page 51 of the *PICkit 3 Starter Kit User's Guide*. Here we cover a straightforward test where we turn on and off each of the four LEDs individually. We could perform this in our code, by controlling each LED directly, but we're going to be a little smarter and use something called a 'right shift' to move through each bit in Port C. We'll get back to that in a moment.

Listing 1: rotating LEDs

```
void main(void) {
    TRISC = 0;
    OSCCON = 0b00111000;
    LATC = 0b00001000;

    while (1) {
        __delay_ms(500);
        LATC >> = 1;
        if(STATUSbits.C)
        LATCbits.LATC3 = 1;
        }
}
```

See Fig.1 for a flow chart of the code we're using in Listing 1. It starts off the same as our Blink program from last month. We begin by setting all of Port C as outputs, then we set our clock to 500kHz using the `OSCCON` register. This register is solely used for setting the internal oscillator. In the next

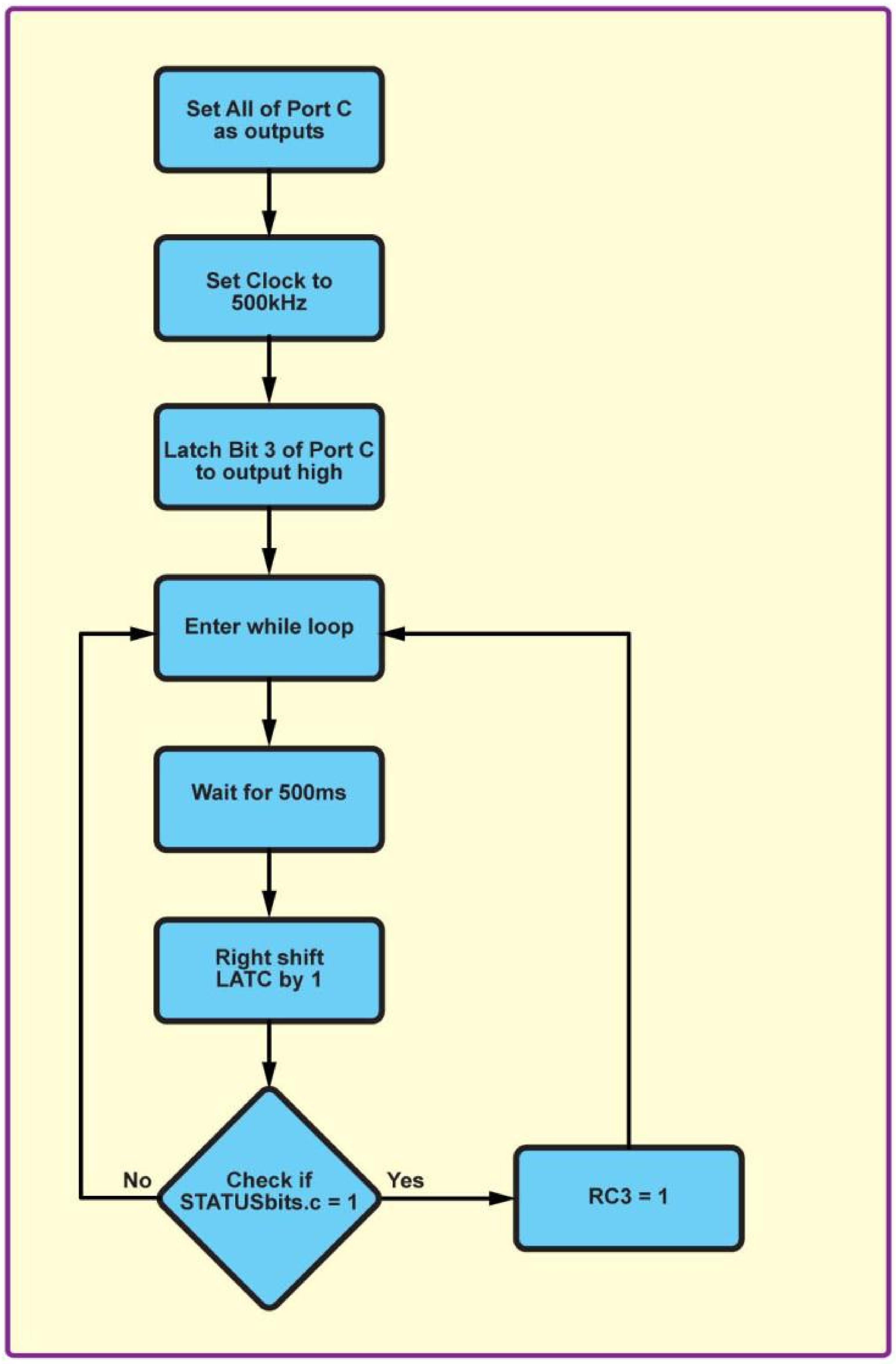
Set All of Port C as outputs
Set Clock to 500kHz
Latch Bit 3 of Port C to output high
Enter while loop
Wait for 500ms
Right shift LATC by 1
Check if STATUSbits.c = 1
No
Yes
RC3 = 1

Fig.1. Lesson 3 – rotate LED flowchart

line, we set all of the bits in Port C as a low output, except for bit 3 (Remember, there are 8 bits in total, but numbered from 0 to 7, where 0 is on the right hand side and bit 7 is on the left hand side. Hence bit 3 is actually the *fourth* from the *right*). The prefix 0b tells us it is a binary number. (This would change to 0x for a hexadecimal number, and without a prefix, it is assumed to be decimal.) Last month, we did this by setting LATC = 0; and then we wrote LATCbits.LATC3 = 1; – the code LATC = 0b00001000; is a shorter way to do this. Functionally, it's exactly the same, except that it's now completed in one instruction instead of two.

Back to the while loop...

Now we enter the while loop. There is a delay of 500ms, which ensures we can see the LED switch. Now for something a little more tricky – our next line (LATC >> = 1;) takes the value in our register LATC (which is 0000 1000 at the start) and we right shift this number by one, in other words we move each bit in the register one space to the right, giving us 0000 0100. Fig.2 shows the right shift in action. Notice the added 0 on the left, which is added every time it is shifted right. Here, >> is the code for right shift (we'd use << if we wanted a left shift) and the = 1 indicates we shift (right) by one bit.

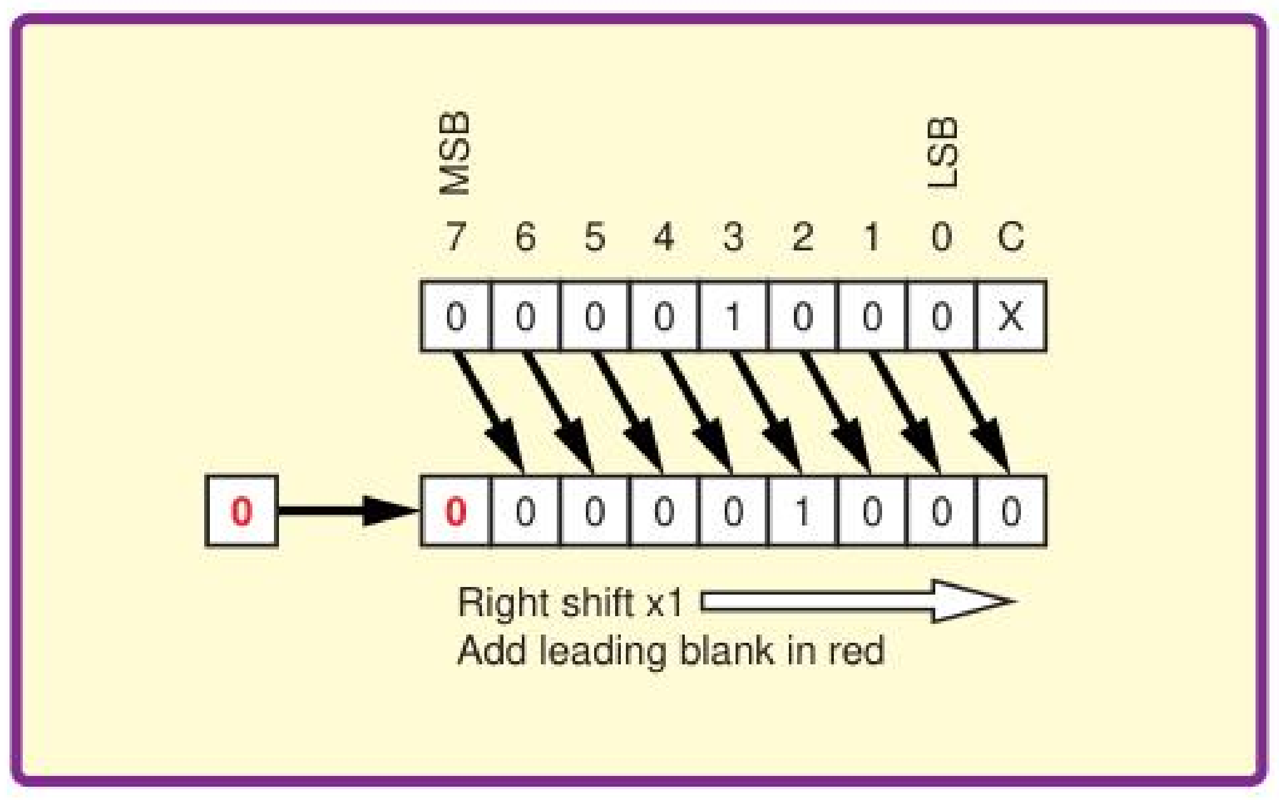

Fig.2. Lesson 3 – right shifting and the carry bit

This right shift operation is an 'arithmetic' operation. This means the output of this operation is stored and tested in our STATUS register before being moved back into our LATC register. The STATUS register checks for a number of conditions, such as zero, digit carry, carry, overflow and negative. The STATUSbit.C allows us to check if there has been a carry in our maths. For example, take the decimal number 255 and add a 1, we get decimal 256. However, with an 8-bit binary number, 255 is 1111 1111, so if we add a 1 to it, we get 0000 0000, which is not 256. In this instance, our carry bit will be set, letting us know that it is actually a 9-bit number, represented by 1 0000 0000. The carry bit gets round the problem of larger numbers when restricted to an 8-bit microcontroller.

Now if we shift our 1 in LATC another three times, we will move the single '1' in the register into the carry register, resulting in: 0000 0000 1, setting the carry bit. This may look odd, the carry bit seems to be to the right of the LSB (least-significant bit). This is a bit confusing, and is a reflection of how PICs implement binary arithmetic, which is a topic we will come back to in the future. For now, just accept that the carry bit has been set.

The code (if(STATUSbits.C)) checks to see if this carry register is set, if it is, then we set bit 3 of Port C back to a 1 and repeat our right shifting again. As we saw earlier, instead of LATCBITS.LATC3=1; we could have used LATC = 0b00001000;. It doesn't matter, which you choose.

Demo Board steps – Make, Compile and Program

Let's get our code running and watch the LEDs rotate.

1) In MPLAB, replace the code in Lesson 2 with the code in Listing 1. (Alternatively open the C project 'rotate' from the downloadable link discussed above.)
2) Connect the PICKit3 Programmer as in Fig.3.
3) Make and Program the the Demo Board by clicking on the green down arrow in the toolbar in MPLAB
4) That's it! Sit back and bask in the glory of twinkling LEDs!

Lesson 4 – Analogue-to-digital conversion

Next, it's time for a subject we will come back to again and again – analogue-to-digital conversion. It can be quite complex and difficult to get right at first, so we will take it slowly. (Ian Bell has looked at ADCs a number of times in *Circuit Surgery*, see Sep-Oct 2012 and May 2016.) So far, we've only looked at setting an output to a high (1) or a low (0). In the physical world, a high would be represented by Vcc (board voltage), which is 5V on our Demo Board. A low is our ground or 0V. In this section, we look at our first analogue (non-binary) input; so instead of trying to figure if it is high or low, we want to try and capture any value in between 0V and 5V. So how do we convert a real-world varying voltage into a bunch of ones and zeros? We capture the analogue real-world value and convert it into a digital value using an analogue-to-digital converter (ADC) via the PIC's built-in ADC input.

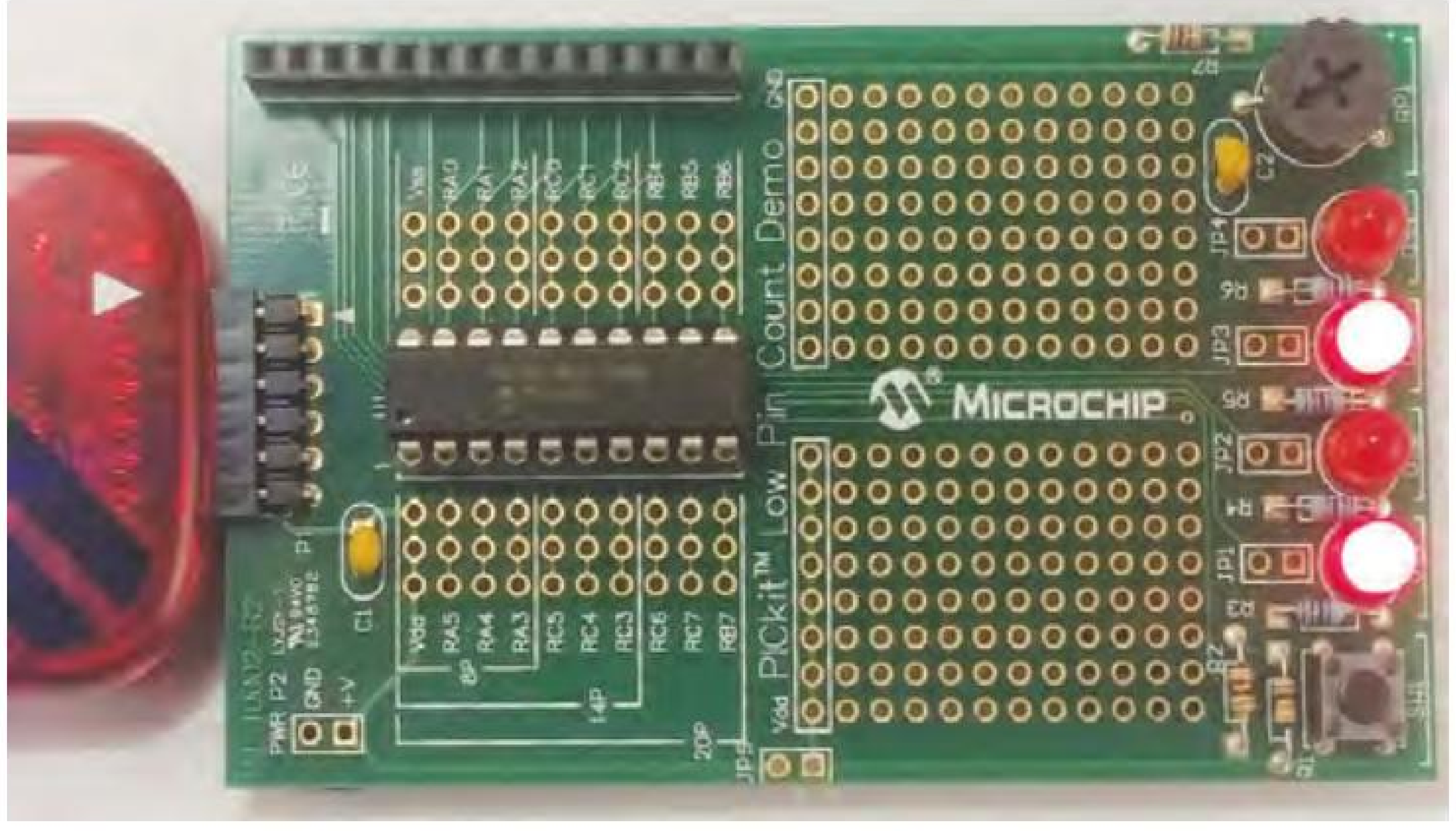

Fig.3. The PICKit Low Pin Count Demo Board running Lesson 4 with LED output 0101

In our PIC, we have a '10-bit' ADC. That means we have 10 bits to describe the voltage in the real world. 10 bits gives us 1024 (2^10 or 2^{10}) different values between 0V and 5V. If we divide our 5V by 1024, we calculate the magnitude of each bit, which is 4.88mV. This is also known as the ADC's 'resolution'. For example, if the output of our ADC is 0b100111000, which is 312 in decimal, then we know the input was voltage of 312 × 4.88mV = 1.52256V.

A few points are worth bearing in mind. Although our real-world varying voltage could take any value between 0V and 5V, our ADC can only measure this voltage in little jumps (the resolution). You can think of it as going from a smooth ramp (the actual voltage) to a staircase (how the ADC sees this voltage), where the height of each step is the ADC's resolution. Do note that although the value of '1.52256' is mathematically correct, the six-digit precision is not representative of what you can really achieve without some very advanced techniques. That's why even expensive digital voltmeters rarely go beyond four digits of precision.

Back to PICs! This lesson will allow us to configure the ADC, run a conversion and read the analogue voltage controlled by the Demo Board's potentiometer RP1 (almost identical to a variable resistor) and display the high-order four bits on the four LEDs. I recommend reading the lesson in the *User's Guide*, which covers the ADC and its inner workings in depth.

Listing 2: analogue-to-digital conversion

```
void main(void) {
        OSCCON = 0b00111000;
        TRISC = 0;
        TRISAbits.TRISA4 = 1;
        ANSELAbits.ANSA4 = 1;
        ADCON0 = 0b00001101;
        ADCON1 = 0b00010000;

        while (1) {
                __delay_us(5);
                GO = 1;
                while (GO) continue;
                LATC = (ADRESH >> 4);
        }
}
```

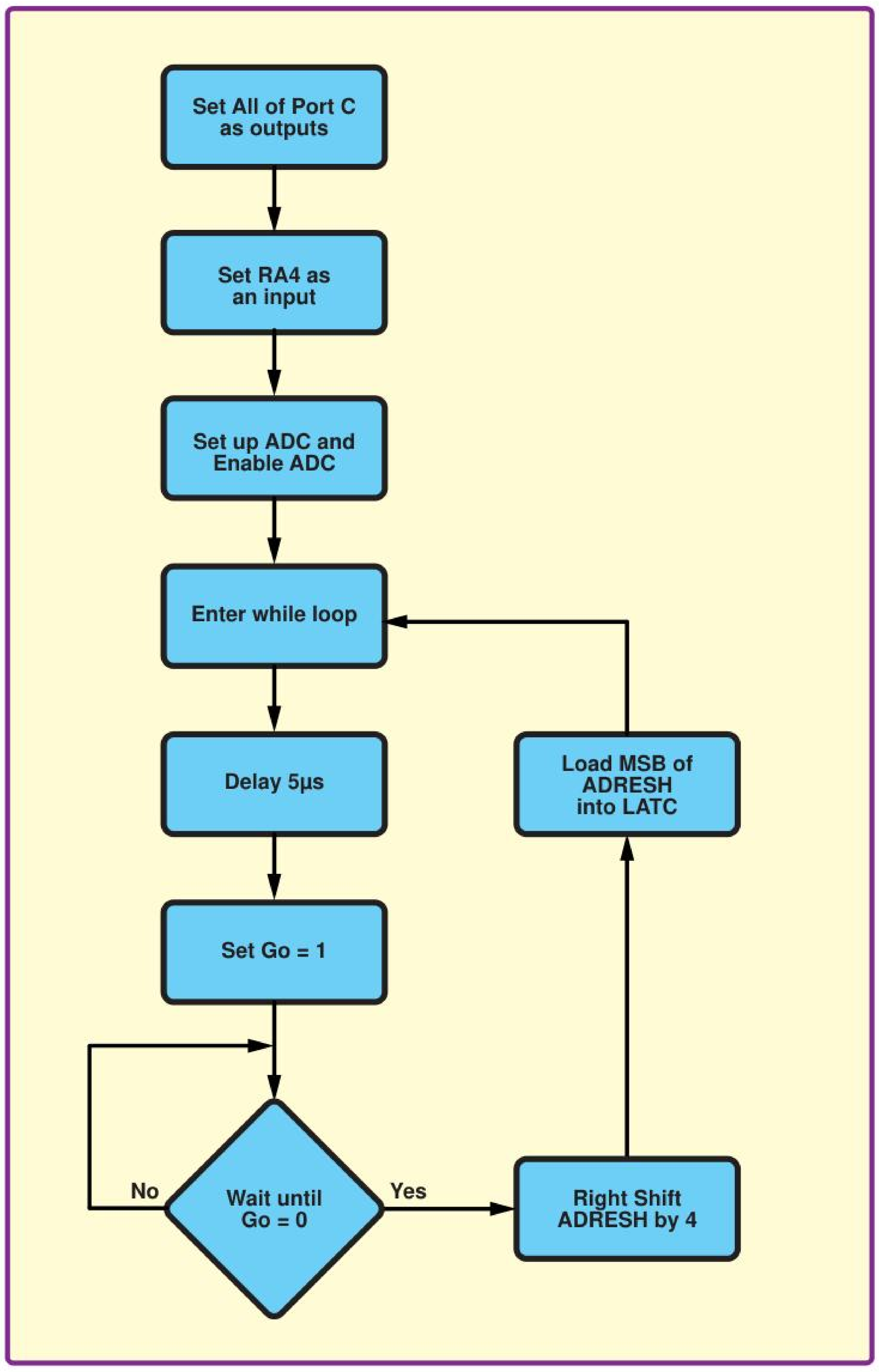

Fig.4. Lesson 4 – analogue-to-digital conversion – flowchart

Examine the code in Listing 2, taken from the downloadable projects mentioned above. First, we set the internal clock (OSCCON) and Port C (TRISC) as in previous lessons. Next, the code sets bit 4 of Port A (`TRISAbits.TRISA4 = 1;`). This is the ADC pin connected to pin 3 on the Demo Board PIC, which is connected to one end of the potentiometer. Next, we meet a new register: ANSEL. This is similar to TRIS and LAT, in that it sets bit 4 of Port A to be an analogue pin when equal to one, or a digital pin when equal to a zero. The two ADCON lines set the ADC's registers for normal operation and enable the ADC conversions to take place automatically. You can find more information on these pins in the PIC16F1829 datasheet on Microchip's website.

LATC								
Bit #	MSB (7)	6	5	4	3	2	1	LSB (0)
LED	–	–	–	–	DS4	DS3	DS2	DS1
Value	0	0	0	0	1	0	0	0

Fig.5. LATC bit mapping to LEDs DS1-4

Next, we come to our first `while` loop. Here, there is a much shorter delay of 5µs, which is all we need for our conversions. Then we have a new word: GO. This is not actually a variable but an internally used register in the PIC16F1829, which is used to determine if the conversion of the ADC from real-world values to a digital value has completed. Once it has been completed, it will exit its own `while` loop and move onto the next line of code.

When the ADC has completed its conversion it will store its value in two 8-bit registers ADRESH and ADRESL. For example, our maximum value is 1023 (5V in the real world), this is represented as 0000 0011 in ADRESH and 1111 1111 in ADRESL. (As an aside, note that the ADCON1 register is set to load these justified left instead of right, which controls how the ADC values are loaded into ADRESH and ADRESL. This means our registers are now 1111 1111 in ADRESH and 1100 0000 in ADRESL. This is just a detail, so don't get bogged down in its overall significance.) Our next line of code right shifts the values in ADRESH by four spaces, giving us 0000 1111. This value is loaded into LATC, thereby lighting all four LEDs. By rotating the potentiometer RP1, different values will be captured and loaded into Port C, illuminating different LED patterns.

Fig.5 shows how LEDs DS1-4 are mapped to the LATC registers. From this diagram, we can work out the four bits loaded from the ADC into our LATC.

To test the program, follow the Make, Compile and Program steps 1 to 4 above. Rotate the potentiometer RP1 in the top right of Fig.3 and watch the LEDs change.

Next month

We've spent quite a few months working through these lessons and gaining a greater understanding of our PICs. I'd like to take a break next month and use our new knowledge to build a physical circuit from scratch. Just as we have been working through the lessons, I will design this simple project using a schematic, a flowchart, a few simple LEDs and a basic format for our code.

Not all of Mike's technology tinkering and discussion makes it to print.

You can follow the rest of it on Twitter at @*MikePOKeeffe*, up on *EPE Chat Zone* as *mikepokeeffe* and from his blog at *mikepokeeffe.blogspot.com*

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AUDIO OUT

By Jake Rothman

Trying out 'Smart Board'

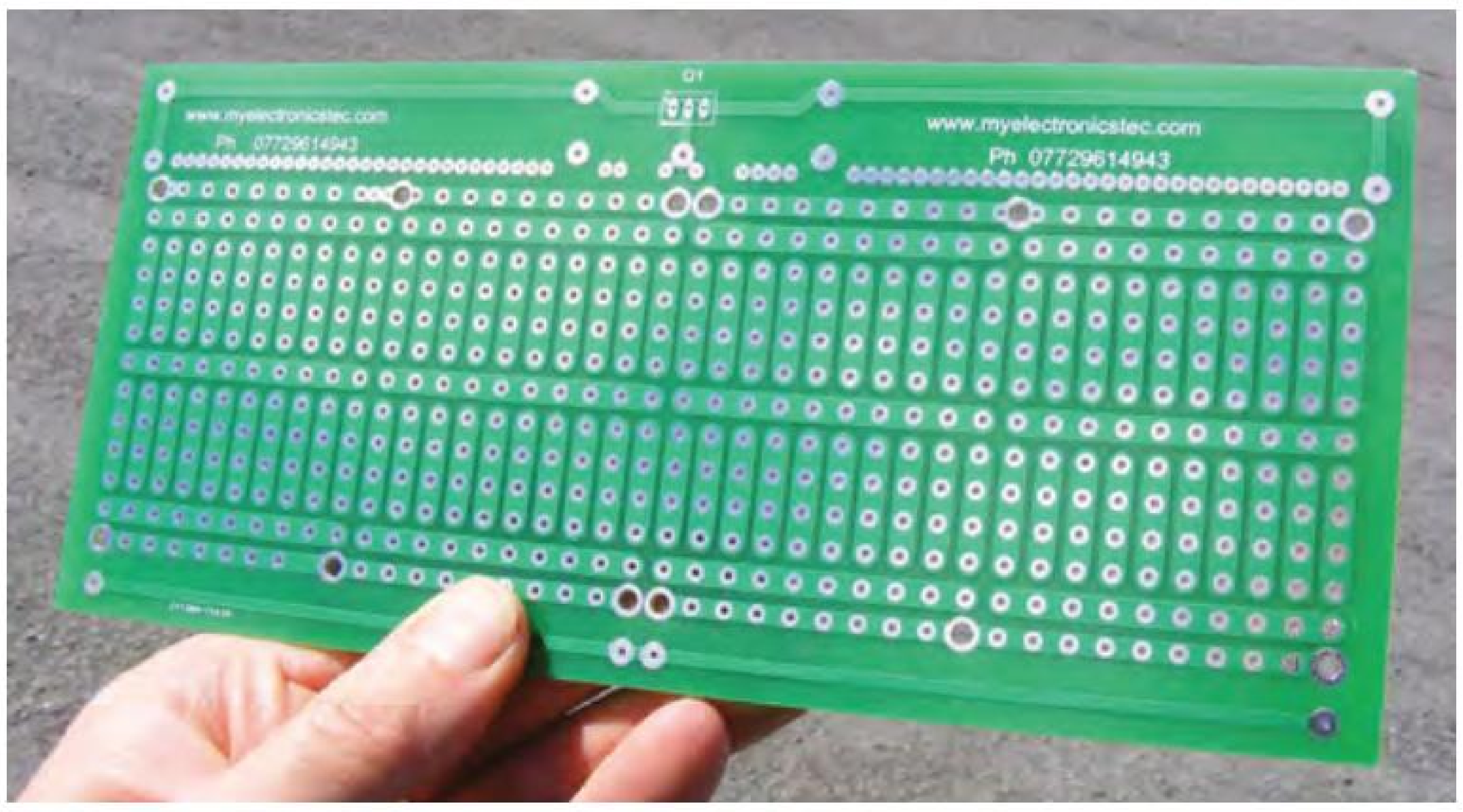


Fig.1. Smart Board – a prototyping board for big components. This view shows the track layout; note the power rails and junction lands.

Let's get one thing out of the way first. In general, I dislike anything prefixed by the word 'smart'. It has come to mean complex and dysfunctional. *However*, this product is anything but – it's a wonderful piece of Yorkshire 'austerity' engineering. Costing only £5 including postage (it was actually designed to fit into a standard letter envelope and weigh less than the maximum 200g) it is even cheaper than Veroboard. Designed by Kevin Riley of **myelectronicstec.com** in Sheffield, it is made from FR4 fibreglass. The only competition I can find is fragile paxolin 0.2-inch stripboard distributed by Rapid (50-5204). It's dimensioned for large analogue components, such as high-voltage capacitors, wire-wound resistors and big inductors. It is effectively a prototyping board to replace tag boards often used in valve amplifiers, power supplies, passive crossovers and other bulky circuitry. Smart Board's track pattern, designed on PCB Wizard is shown in Fig.1.

Austerity audio

So, how does the Smart Board perform? Well, I decided to put it to a harsh test and build a good cheap valve amp. How cheap? Well, most people can't afford a £5k valve amp, so how about one that costs around £25? Nobody wants old TV valves anymore and they can be picked up for about a pound, so forget your gold-plated KT66s, I'm using PCL84 triode-pentodes picked up from Bardwell's (in Sheffield) surplus list for 60p a few years ago. The same circuit topology will work with other valves, such as the PCL82, 3, 5 and 6, with changes to the pentode cathode resistor R, anode load impedance and heater voltage. This design will only give about 560mW into 8-15Ω, so it is ideal for low volume listening, headphones and overdriven guitar practice/studio 'micing'. The PCL84 has an anode dissipation of only 4W and it is run at 3.75W, assuming a 250V power rail and a 270Ω cathode resistor. Total heat dissipation from the valve is 8.25W including the heater, so it needs to be spaced from the board.

Proper output transformers cost a fortune, but here I've used 3VA 2 × 6V mains transformers that mount directly on the 0.2-inch pitch on the Smart Board. The valve needs an anode load of 10kΩ to 18kΩ. The STC mains transformers gave a measured impedance of 12kΩ with an 8Ω load connected to the secondaries wired in parallel, with the primaries in series. The frequency response was 46Hz to 12kHz between the –3dB points. I did try an Eddystone radio transformer obtained from a radio rally, a Parmeko 4967P having a primary impedance of 16kΩ. It gave Hi-Fi performance and 900mW output.

Valve power supplies are a pain, but we can use a standard isolation transformer for the high tension (HT) and a 15V 'wall-wart' for the low tension (LT) heaters. Power requirements are 20mA 200V to 250V HT and 300mA 15V LT. Danbury sell a suitable transformer, the ST29G-DB426. I used a cheap Bardwell's 43-0-43V / 8-0-8V transformer where the HT was derived using a voltage doubler, as shown in Fig.2, giving 200V. I used multiple 22µF 250V radial capacitors, since the tag types wouldn't fit. The power output was 450mW with the cathode resistor R15 changed to 130Ω. Another trick is to wire two 15V transformers back-to-back taking the heater from the middle before stepping up again for the HT.

Hybrid circuitry

Older readers will remember the televisions of the 1970s that had a combination of valves and transistors. A small-signal triode with an output pentode does not give sufficient gain for a good overdriven guitar sound. To avoid the use of another valve for the pre-amp stage, a JFET is cascoded with the input triode. The full circuit is shown in Fig.3. This is a very useful technique that gives less noise than the equivalent extra valve, while still retaining the high input impedance that guitars need. The rest of the circuit is conventional. An optional Zobel network (C12 and R17) can be placed across the output transformer primary to soften the clipping on overdriven guitar. Note, C12 must be rated at 630V

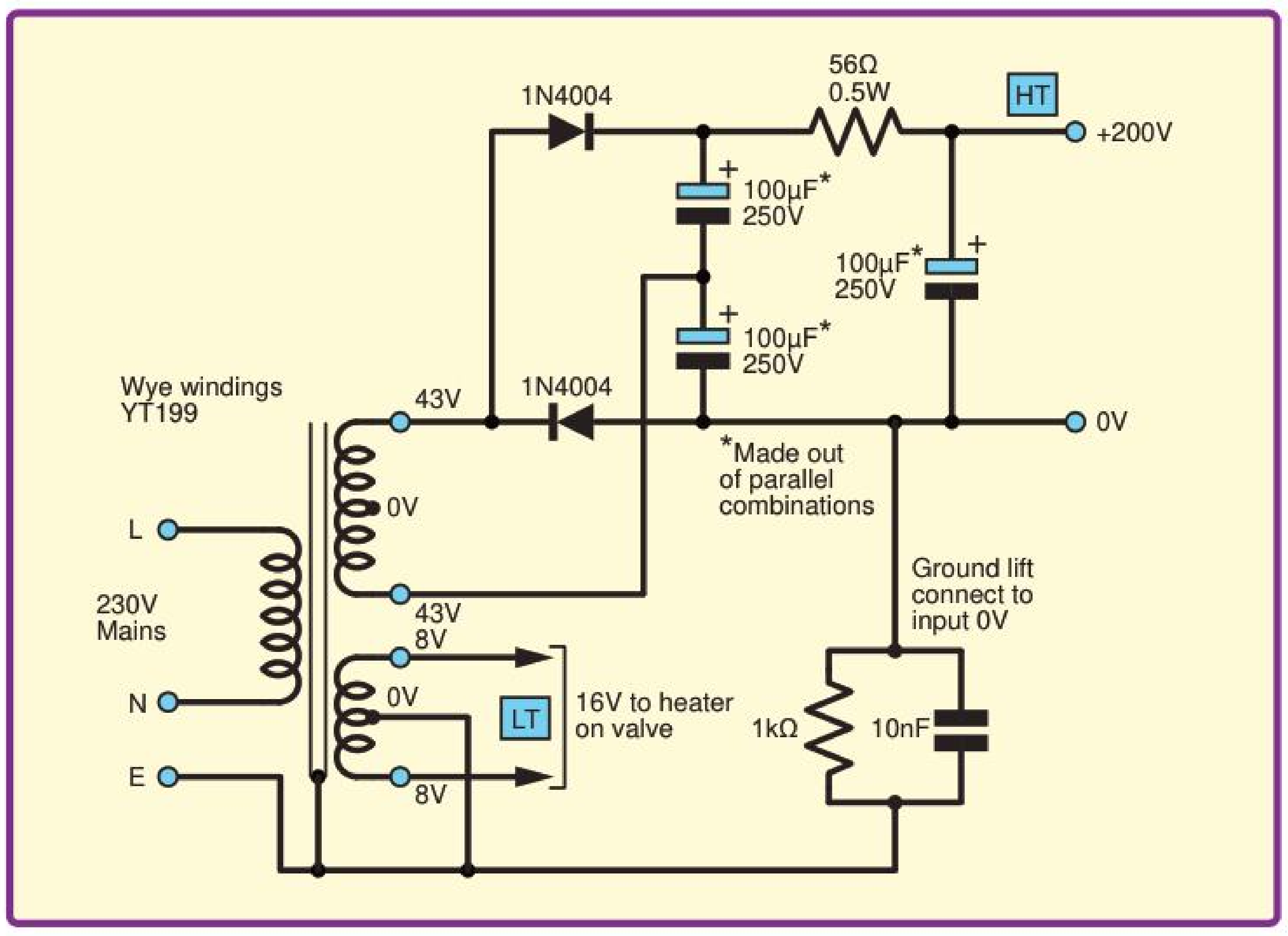


Fig.2. One way of getting the high voltage required, use a voltage doubler. The transformer was a surplus item.

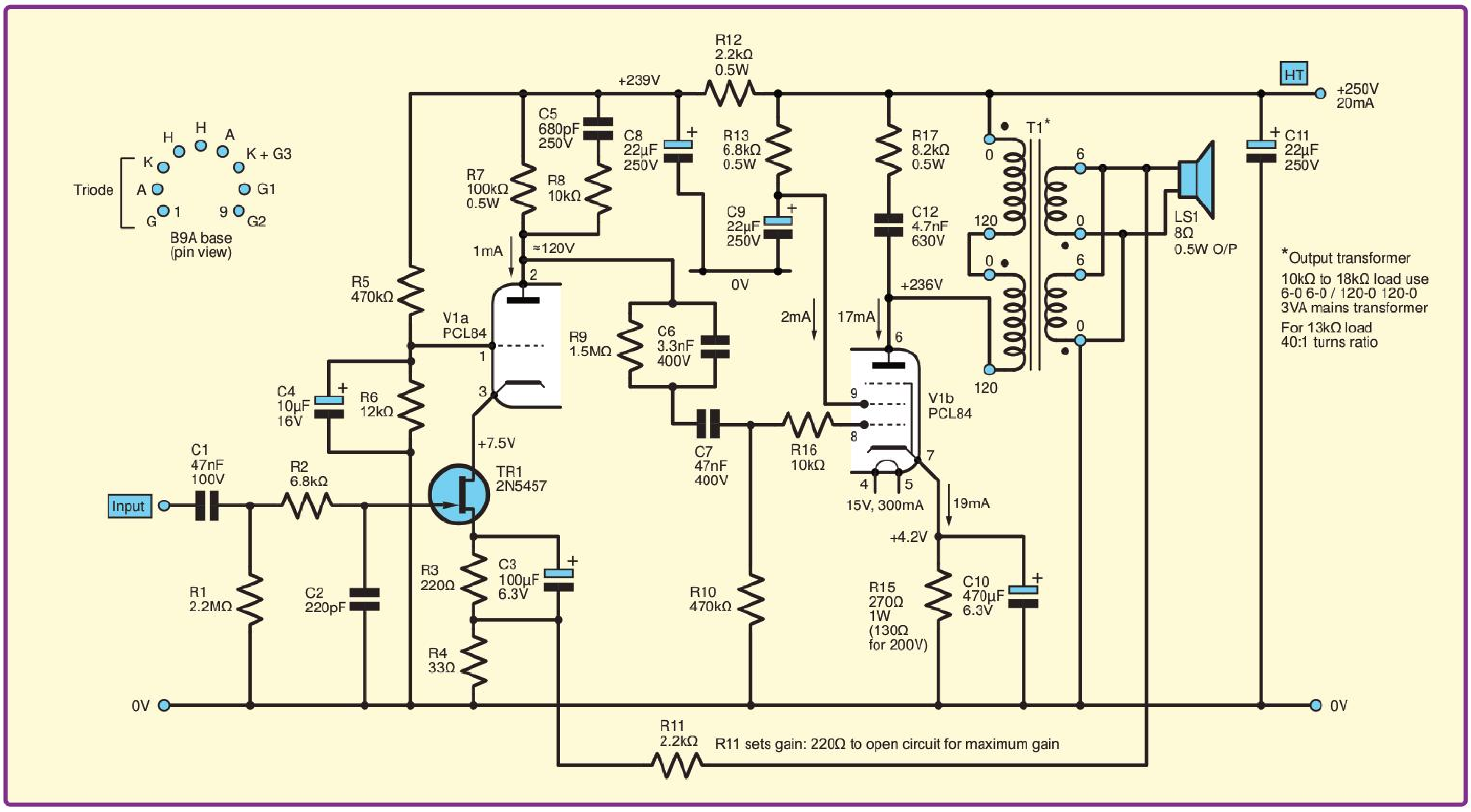

R12
2.2kΩ
0.5W
+239V
HT
+250V
20mA
H
H
A
K
K + G3
Triode
A
G1
G
1
9
G2
B9A base
(pin view)
C5
680pF
250V
C8
22µF
250V
R13
6.8kΩ
0.5W
R17
8.2kΩ
0.5W
T1*
C11
22µF
250V
R7
100kΩ
0.5W
R8
10kΩ
C9
22µF
250V
C12
4.7nF
630V
LS1
8Ω
0.5W O/P
0
6
120
0
0
6
0
120
*Output transformer
10kΩ to 18kΩ load use
6-0 6-0 / 120-0 120-0
3VA mains transformer
For 13kΩ load
40:1 turns ratio
1mA
≈120V
2
0V
+236V
R5
470kΩ
V1a
PCL84
R9
1.5MΩ
C6
3.3nF
400V
2mA
17mA
6
1
3
9
V1b
PCL84
8
C4
10µF
16V
R6
12kΩ
+7.5V
C7
47nF
400V
R16
10kΩ
7
C1
47nF
100V
R2
6.8kΩ
TR1
2N5457
4
5
15V, 300mA
19mA
Input
+4.2V
R3
220Ω
C3
100µF
6.3V
R10
470kΩ
R15
270Ω
1W
(130Ω
for 200V)
C10
470µF
6.3V
R1
2.2MΩ
C2
220pF
R4
33Ω
0V
0V
R11
2.2kΩ
R11 sets gain: 220Ω to open circuit for maximum gain

Fig.3. No need to spend thousands – a low-power valve amplifier using a cheap TV valve.

due to high back EMF from the output transformer's primary inductance. Almost any low-current JFET may be used, but the higher the transconductance, the higher the open-loop gain.

Oscillations and hum

If the output is the wrong phase due to the output transformer wiring, the negative feedback will become positive. If it squeals, flip it. Varying the feedback resistor can be used to alter the gain. It can be reduced to 220Ω or omitted entirely for a dirty guitar sound. The compensation networks may have to be tweaked to prevent oscillation with negative feedback if different output transformers are used. C5 and R8 provide the high frequency roll off and C6 and R9 the low frequency.

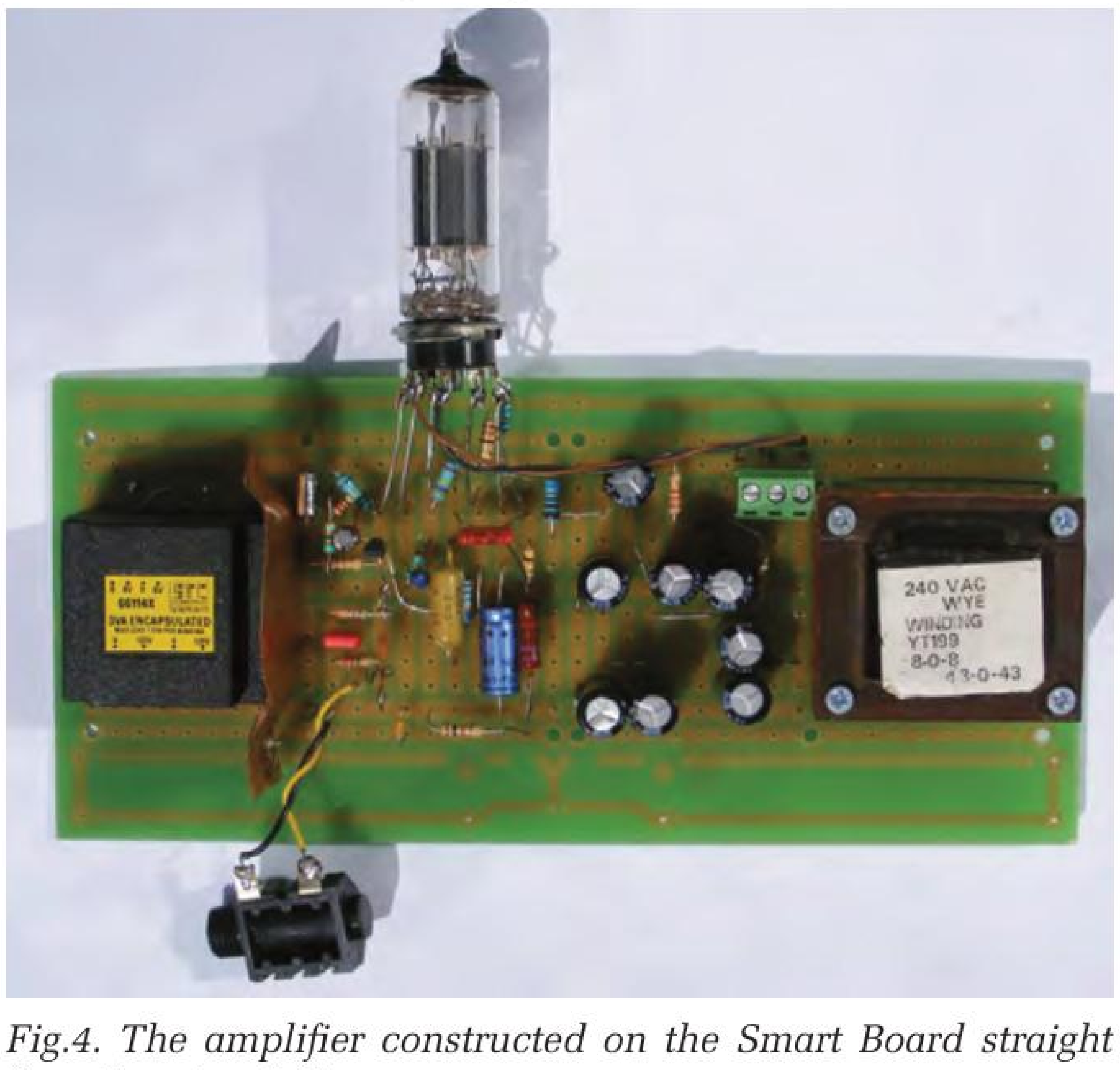

240 VAC
WYE
WINDING
YT199
8-0-8
13-0-43

Fig.4. The amplifier constructed on the Smart Board straight from the circuit diagram.

The transformers are at opposite sides of the board to avoid magnetic hum coupling. Also, since the heater is AC, it can cause hum. Always twist the heater wiring, as shown in the photo of the completed amplifier in Fig.4. An earthed centre-tapped heater winding minimises hum. If not available, a pair of 330Ω resistors can be used to make an artificial tap, which is then grounded.

Skeletons in the cupboard

I used to make horrid 'skeleton' constructions for experimental valve circuits (see Fig.5). The Smart Board allows a much more permanent and reliable assembly to be made. I've not provided a board layout drawing of this amplifier since it's a prototype and I'm sure readers will want to do their own layouts – possibly much neater! I encountered some high frequency instability, which was cured by placing a copper screen between the input stage and output transformer which were too close.

Some of the holes in the Smart Board are a bit too small for my taste – there is a whole row of 0.8mm holes I couldn't fit anything in, except small transistors. (I realised later that these holes are good for 0.1-inch board inter connectors. All the pads are isolated so it's a way of connecting another smaller board, say a microcontroller, with wire links on the underside.) I did like the M3 holes, which were all connected together allowing easy earthing and mounting.

One small gripe, well an observation really: the mounting-hole strips are not joined in the middle, although it looks like they are. This caused me a hard-to-trace earthing fault when mounting the unit in a metal box.

I do hope Kevin will design a valve socket board – the 'Valveboard'? – to complement the Smart Board. With today's overemphasis on miniaturisation this product is unique and will assist many design engineers. All in all, *I really enjoyed using and strongly recommend the Smart Board*, and I'm sure the distributors will find it worth stocking. I've got loads of ideas to test – do I get a good quantity discount on 10?!

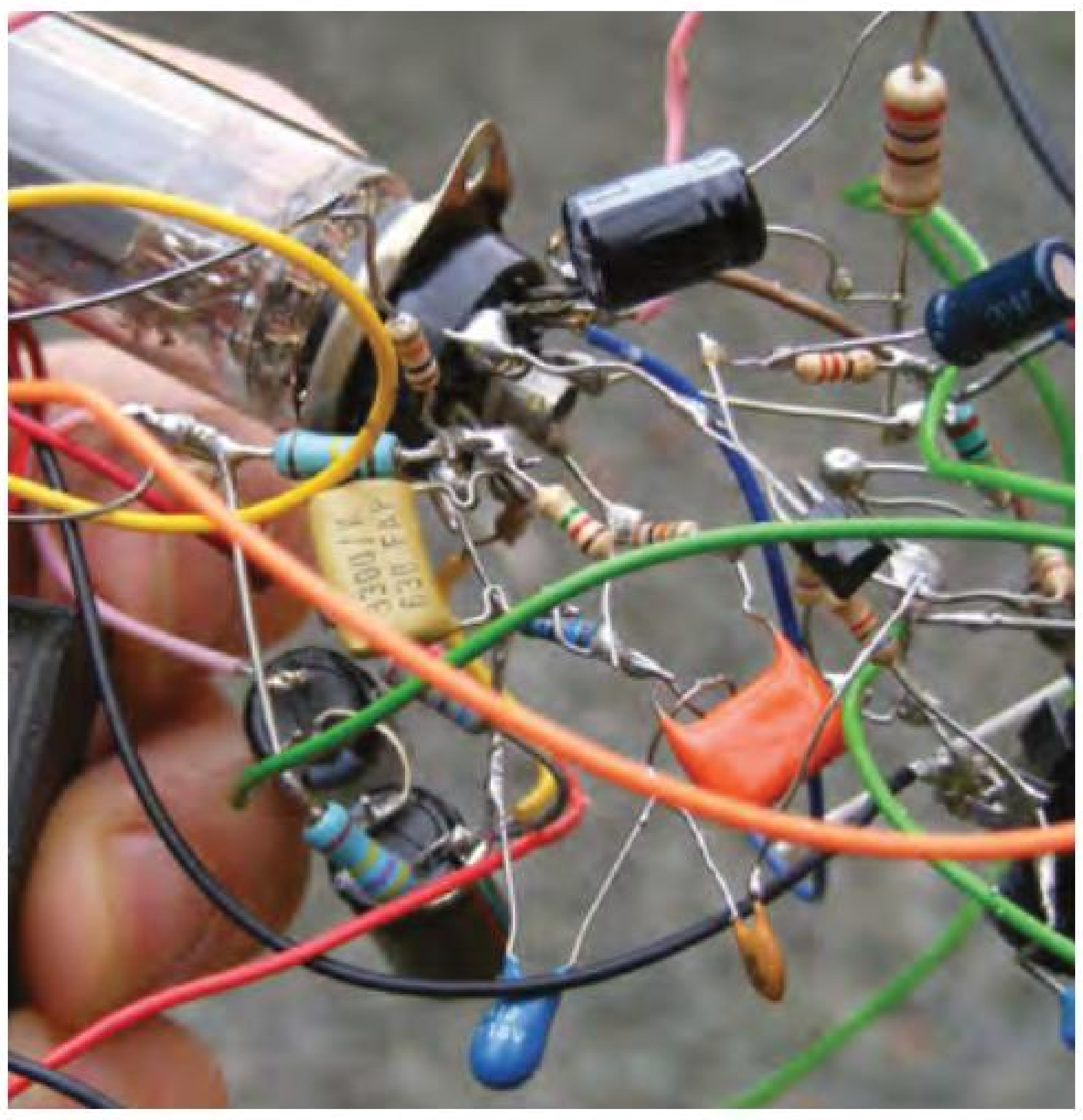
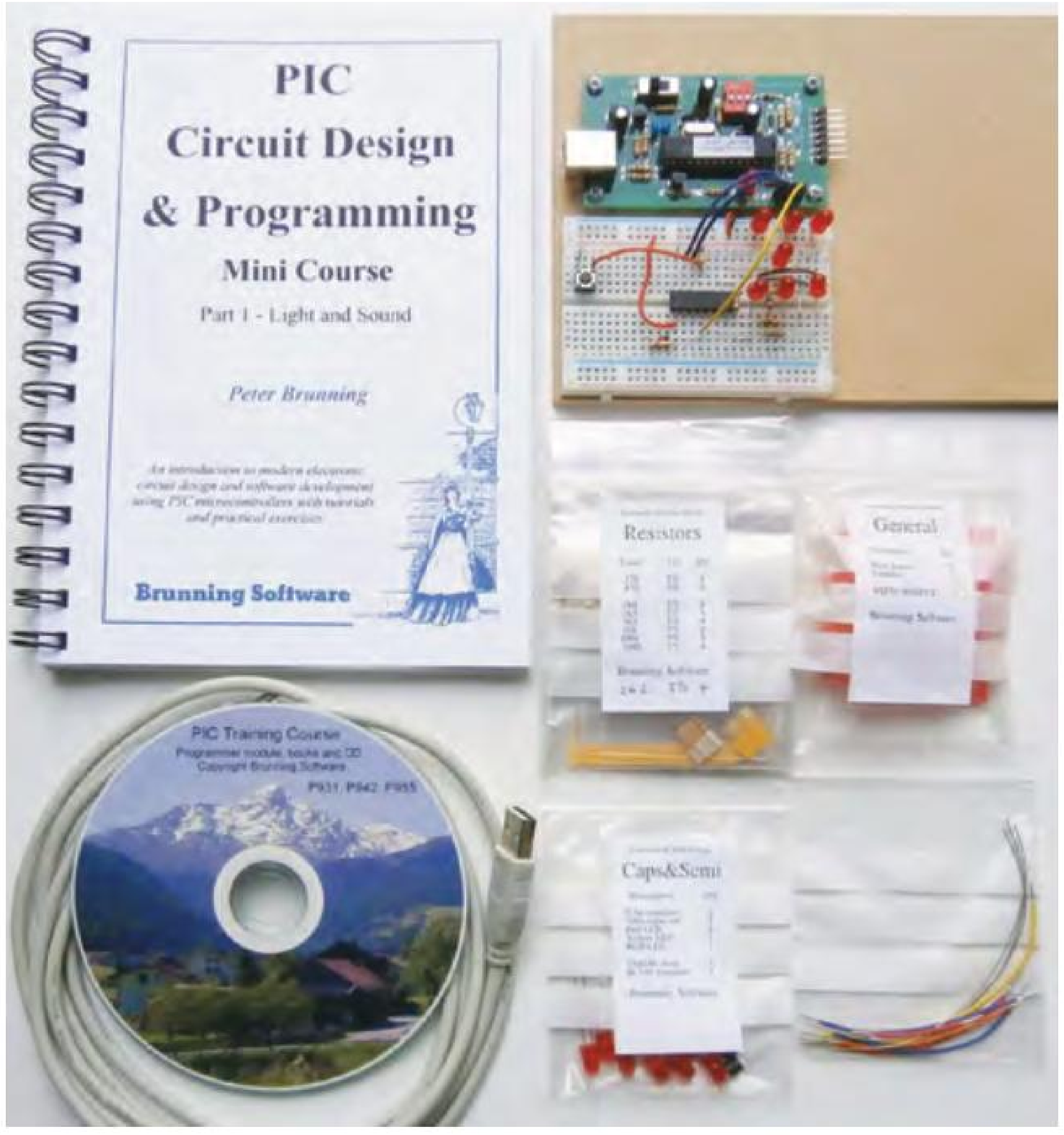


Fig.5. Skeleton version of a valve amplifier – Smart Board is definitely a preferable construction route.

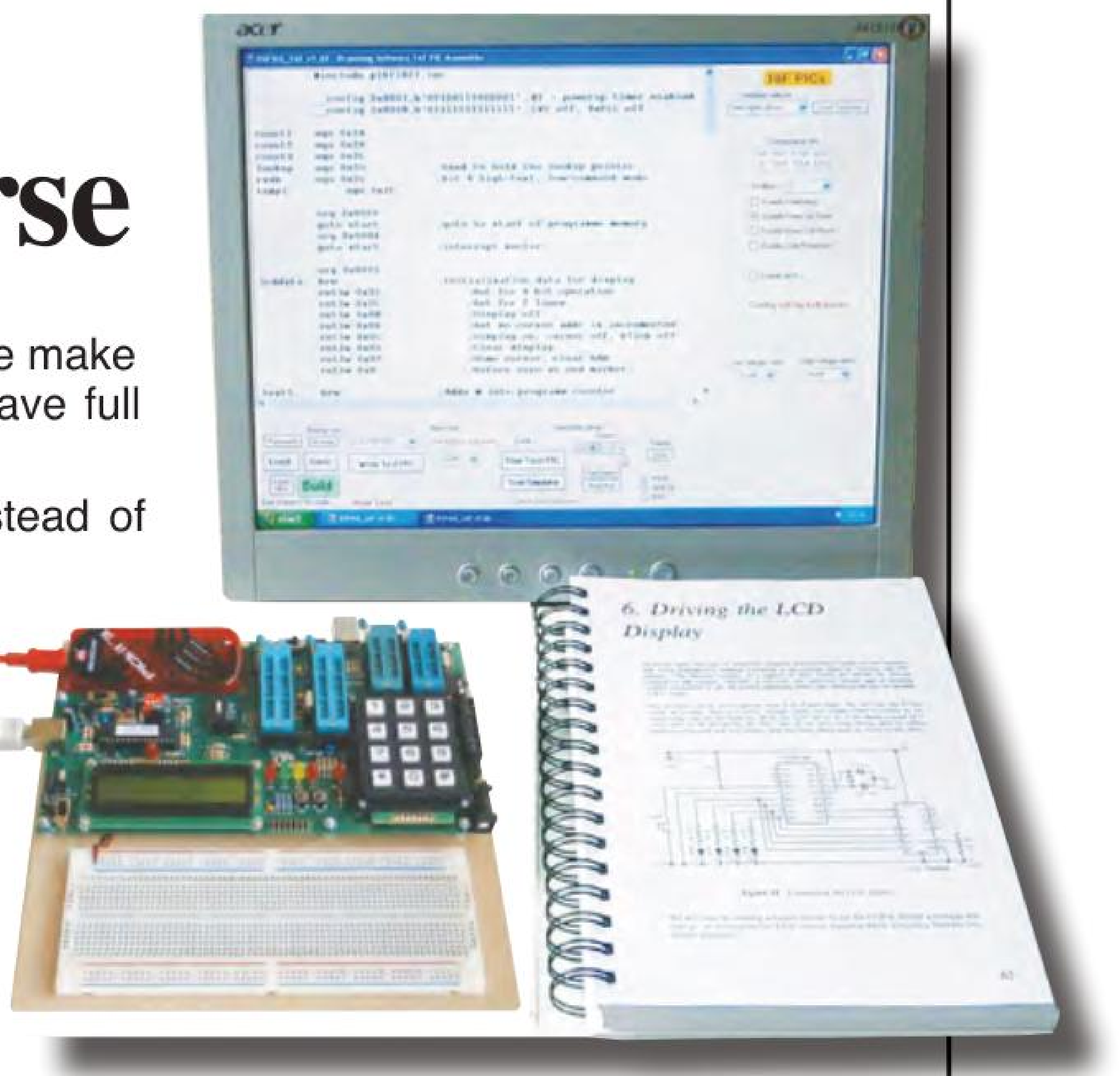
PIC Circuit Design & Programming Mini Course

by Peter Brunning



Our new mini course uses the same well proven training system as our P955H but the two courses have different content and so are mutually beneficial. Part 1 of the mini course is now ready and starts by introducing the fundamental components which are used in electronic circuit design. This is done by experimenting with simple circuits which you build on the plugboard. In the next chapter the manual flash LED circuit is expanded to use a PIC microcontroller to automatically flash the LED. You build the circuit then type in the software which tells the PIC how to turn on the LED. Then just as you are thinking it is too easy you are asked to change the LED circuit to a different output pin and to rewrite the software. The book continues in this way with tutorials and exercises. You learn to use delay routines and a push button then you are asked to create a push to light system with the LED staying on for one minute. You are being taught how to outline and develop your own programmes. Then you wire an RGB LED to the PIC and experiment with programmes to light the Red Green Blue LEDs individually and in various combinations to create the colours of the rainbow. We change tack and you wire a simple sounder circuit. You type in instructions to create a beep then expand this to create a siren. You learn to set the tone to true concert pitch. In the final tutorial you wire LEDs to form the dots for a dice machine, type in the outline programme then develop it to produce a random result. Mini course part 1 is £39 which includes P205 PIC programmer with plugboard, pack of components with leads and links, 14 pin PIC16F1823, CD of software, 124 page book (210 × 115mm), USB to PC lead, and postage to a UK address.

The Brunning Software P955H PIC Training Course



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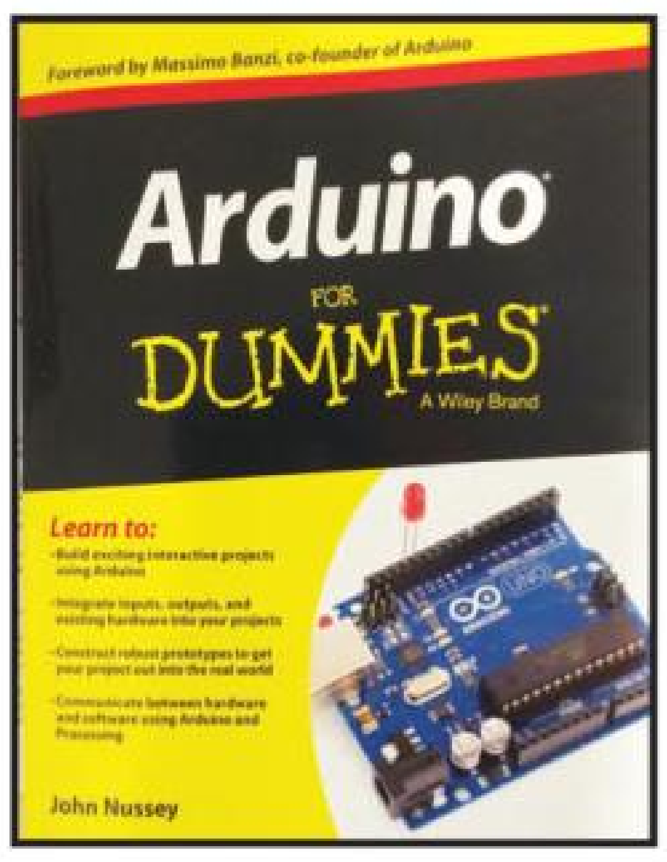
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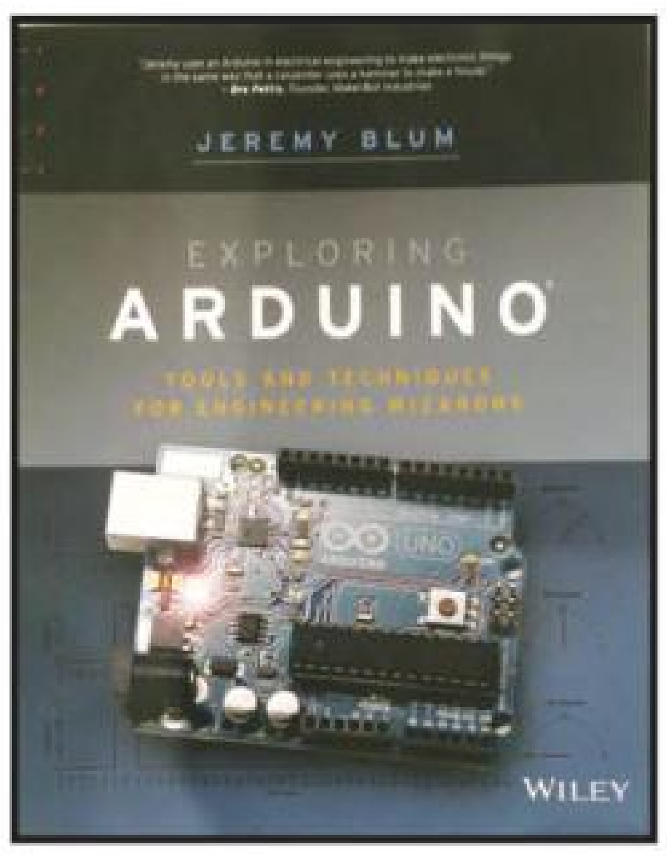
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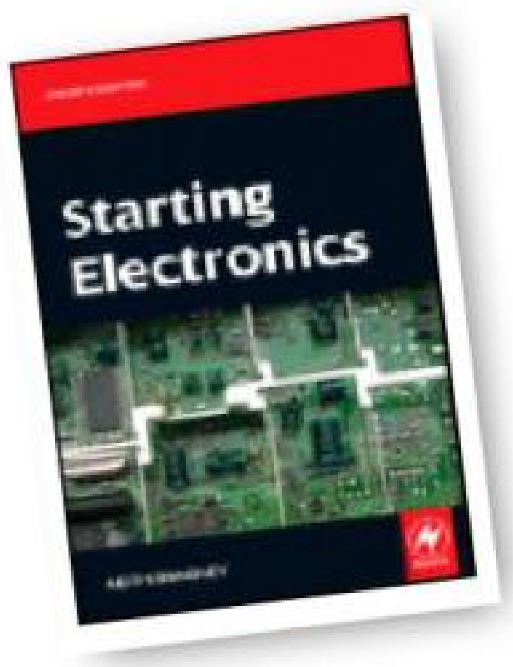
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Practically Speaking

Robert Penfold looks at the Techniques of Actually Doing it!

Be prepared

WHILE ELECTRONIC project building is probably not something that most people would think of as a seasonal pastime, to some extent it is. People tend to pursue outdoor activities in the summer when the weather, hopefully, is conducive to such things. When it's warm, electronics tends to 'take a back seat' and is undertaken less enthusiastically than in the colder parts of the year. For those of us in the northern hemisphere it will still be late summer when this issue of *EPE* is on the bookstalls, but the days will be drawing in, and the autumn will not be far away. It will soon be the start of a new electronic project building season, and newcomers to the hobby will be thinking about building their first project.

When starting any new pastime, the first task is to make sure that you are fully prepared. In the case of electronics, this does not just mean getting all the components for your first project. You need to have the tools for the job, plus a few other essential items. While you could buy all the components and then obtain any tools and materials as building progresses, this would be a very slow and frustrating approach. It is likely the first project would never be completed, and it would also be the last one attempted!

Odd and ends

When buying the main components for a project it is easy to forget the minor items that are just as essential. First and foremost, you will not get far without some solder. Various types of solder are available, many of which are not intended for electrical work, so make sure that the solder you obtain is designed specifically for electrical and electronic applications.

These days, electrical solder can be obtained in various forms, but is mainly available as pastes and wires. The pastes are intended for use with surface-mount components and circuit boards, but initially it is advisable to steer clear of this construction method. In its modern form, surface-mount construction is intended for use in automated production lines, and not for hand-assembled one-off projects. It is certainly possible to build surface-mount boards by hand, but the minute components and pads on the circuit boards make it difficult for the inexperienced. Also, some specialised and expensive equipment is often required.

It is the solder in wire form that is required for 'normal' electronic construction work. Choosing electrical solder used to be easy, because there was only one type generally available. This was solder that contained 60 per cent tin and 40 per cent lead, but something with a high lead content is now considered to be a health hazard and detrimental to the environment. Consequently, in many countries, solder that has a significant lead content is now banned from use in commercially produced equipment. In the EU it can still be used when building DIY equipment, and for renovating or repairing old electronic items. Lead-free solder can now be obtained, but lead-based solders are still readily available and in widespread use.

Ideally, the lead-free variety would be a direct replacement for lead-based solders, but there is an important difference between the two. Lead-based solders melt at a relatively low temperature of around 180 to 190°C. Most lead-free solders are virtually pure tin, and melt at a significantly higher temperature of around 230°C. This is not purely academic. Soldering irons intended for use with lead-based solders will not necessarily work well with lead-free solders. In fact, there is no guarantee that the operating temperature of such an iron will be high enough to reliably melt lead-free solder. Another point to bear in mind is that lead-free solders tend to wear and corrode the tip of the iron more than the lead-based type. An iron should be fitted with a suitable bit if it will be used with lead-free solder. Otherwise the bit might need to be replaced far more often than usual.

One solution to the temperature problem is to use a solder station that includes a temperature control for the iron. The bit temperature can then be adjusted to suit either type of solder, but equipment of this type tends to be quite expensive. The less expensive solution is to buy a good but simple soldering iron, and buy the type of solder it is designed to handle. It might be reasonably compatible with both types of solder, and most non-temperature-controlled irons seem to operate at relatively high temperatures. Some very cheap irons even struggle with lead-based solder, and are best avoided.

Lead-based solders are generally easier to work with, and are probably the better choice for beginners. If you feel it is important to have a 'green' solution, there are actually lead-free solders that have relatively low melting points, and are designed to be used as direct replacements for lead-based solders. These mostly contain a small percentage of silver, and are therefore relatively expensive. In fact, they typically cost almost twice as much as equivalent lead-based solders.

Gauge the situation

Wire solders are available in various thicknesses. As one would probably expect, the thinner gauges are better for small joints, and the thicker ones are easier to use for larger joints. Using thick solder for small joints tends to result in too much solder being applied, possibly causing short-circuits between adjacent pads on the circuit board. With thin solder and large joints there is a likelihood of so-called 'dry' joints occurring, with too little solder being applied.

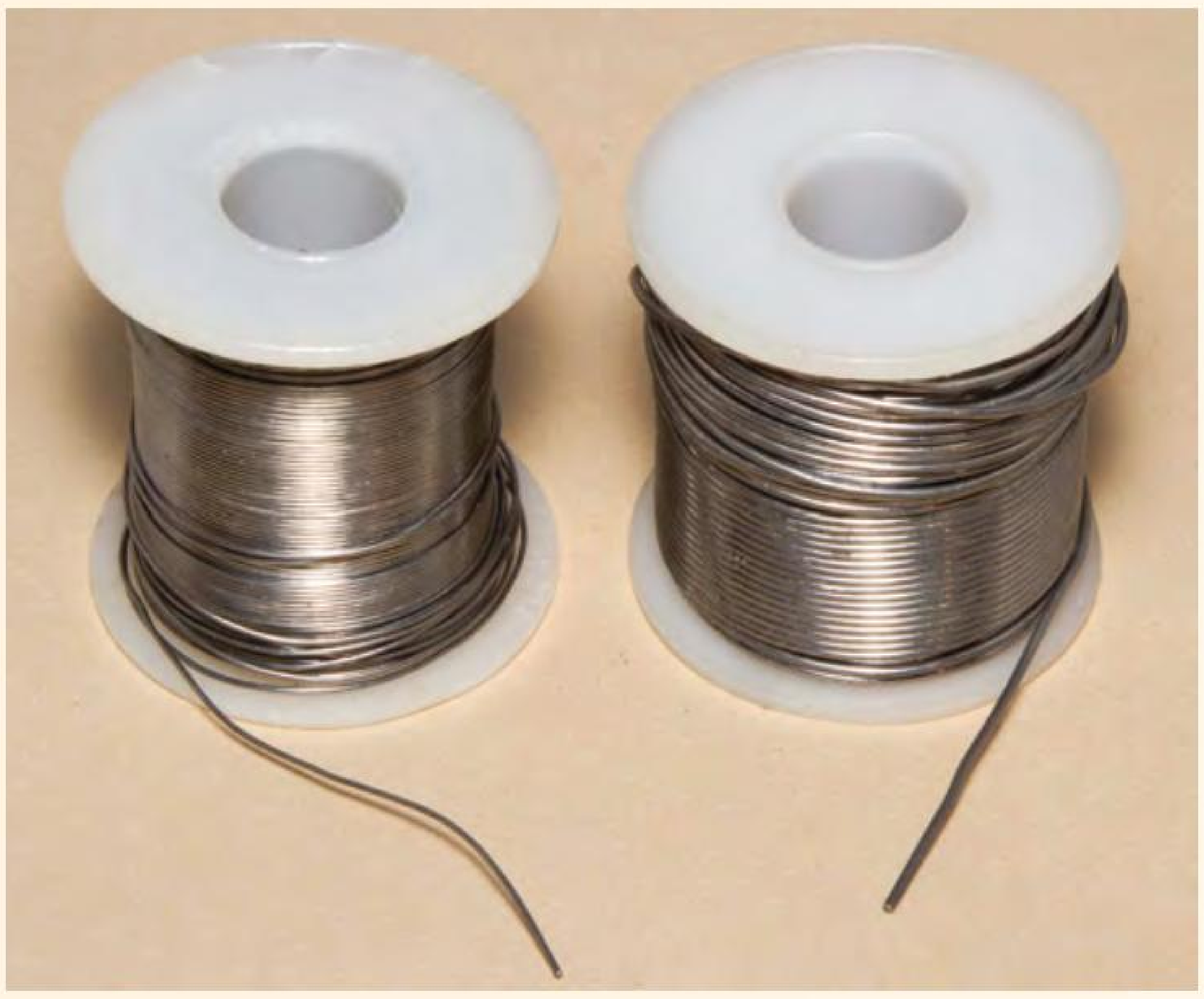


Fig.1. Wire solder with flux cores is needed for most electronic project construction. Shown here, 1.2mm-diameter solder on the left and the 3mm-diameter variety on the right

Modern electronics has a preponderance of tiny soldered connections, and it is therefore a thin gauge of solder that will be needed most of the time. Solder with a diameter of around 1-1.2mm is ideal (Fig.1 left). It is useful to have some thicker solder of around 2-3mm in diameter (Fig.1 right) for the occasional larger joint. Initially, a relatively small amount of thin solder will suffice, but before too long it is worth investing in one of the larger reels (250g or more). The cost per metre is generally much lower when buying larger quantities, and it avoids the frustration of running out of solder with a project 99 per cent finished.

State of flux

A low quality soldered connection is likely to be produced if there is any corrosion or other contamination on the two surfaces to be joined. Physically cleaning the two surfaces prior to making a connection should only be necessary in extreme cases. Small amounts of corrosion are normally handled using chemical cleaning in the form of flux. This cleans the surfaces, helps to prevent the heat from the iron producing oxidation, and generally helps the solder to flow properly. This produces physically strong joints that also provide good electrical connections.

Flux is available from electronic component suppliers, but it is intended for use with some types of surface-mount construction. Wire solders normally have built-in cores of flux, and no additional flux is required. Only use solder that does have the flux built-in.

Wireless

The modern trend is for everything, as far as possible, to be mounted on the circuit board, and the hard wiring to be kept to an absolute minimum. Even so, it is likely that some connecting wire will be needed before too long. With the more specialised cables, such as audio screened and coaxial ('coax') types it is better to buy them as and when required, but some ordinary connecting wire should be obtained before you start building anything.

Simple insulated electrical wires fall into two main categories, which are the single strand and multi-core varieties. While the single-strand type does have its advantages, it is relatively easy to damage it when stripping the insulation, and the multi-strand variety is generally considered to be the better choice for most project wiring. Ordinary connecting wire, which is also known as 'hook-up' or 'equipment' wire, will usually include something like '12/0.1' in its description. In this example it has 12 strands of 0.1mm diameter wire.

Most electronic projects operate at low currents, and any general-purpose multi-strand equipment wire will normally suffice. Bear in mind that the thinner connecting wires can only handle currents of up to about 0.5A (500mA), and that they might be inadequate for projects that involve high currents. A medium-duty wire such as the popular 7/0.2 type is probably a better choice for general project wiring. Thicker connecting wire need only be obtained as and when it is required.

Tools of the trade

With practically any creative hobby it is necessary to obtain some 'tools of the trade' before getting started. Electronic project construction is certainly no exception to this. Some of the tools required are the sort of thing that can be found in a typical household toolbox, but many are not. A soldering iron suitable for electronic work is probably not something that will be found in the average toolbox. As already pointed out, it is not really necessary to have expensive soldering stations.

A small electric iron having a rating of about 15 to 20W (Fig.2 top) is the normal choice for electronic project construction. A matching stand is also needed, and there are

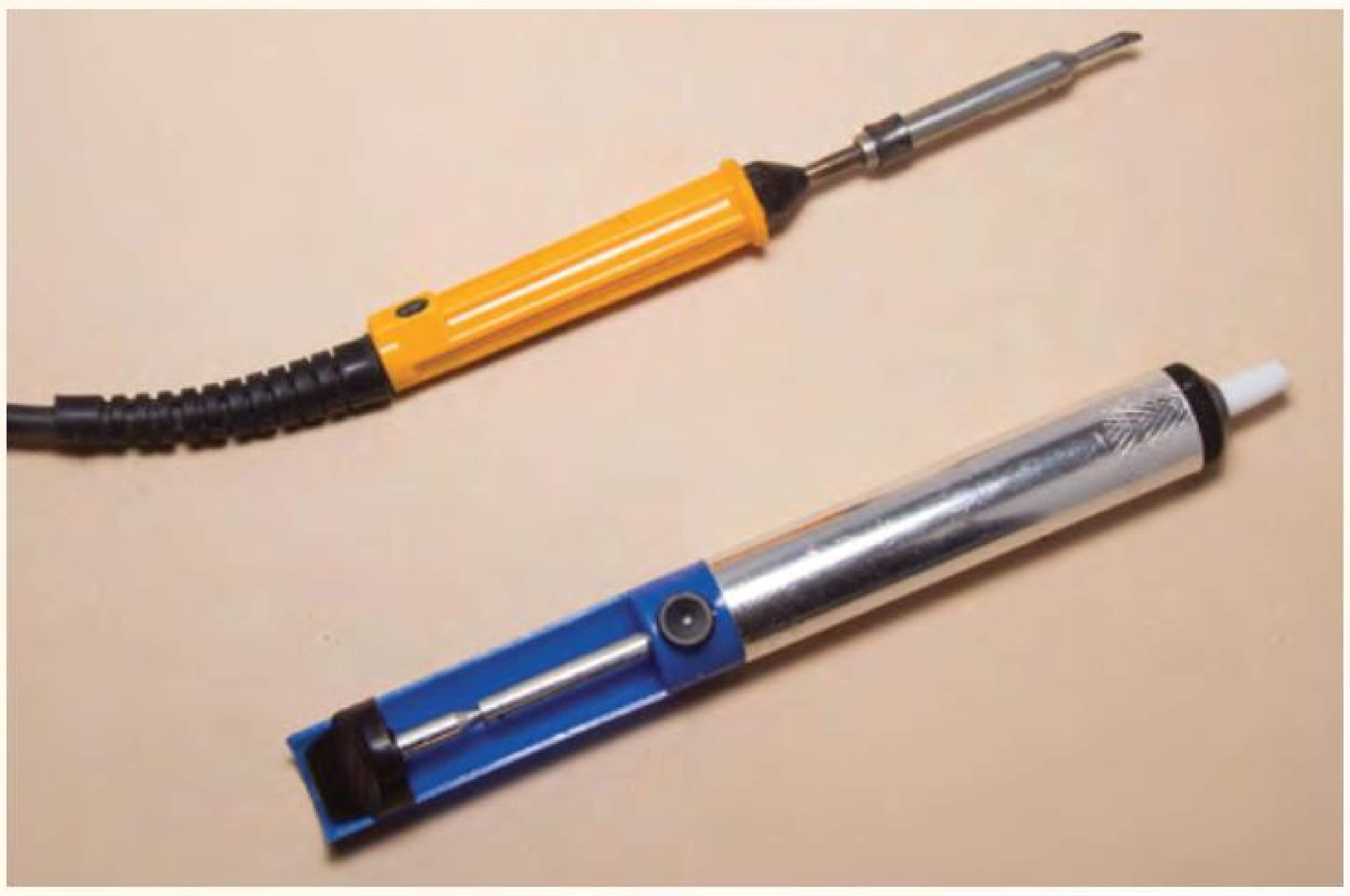
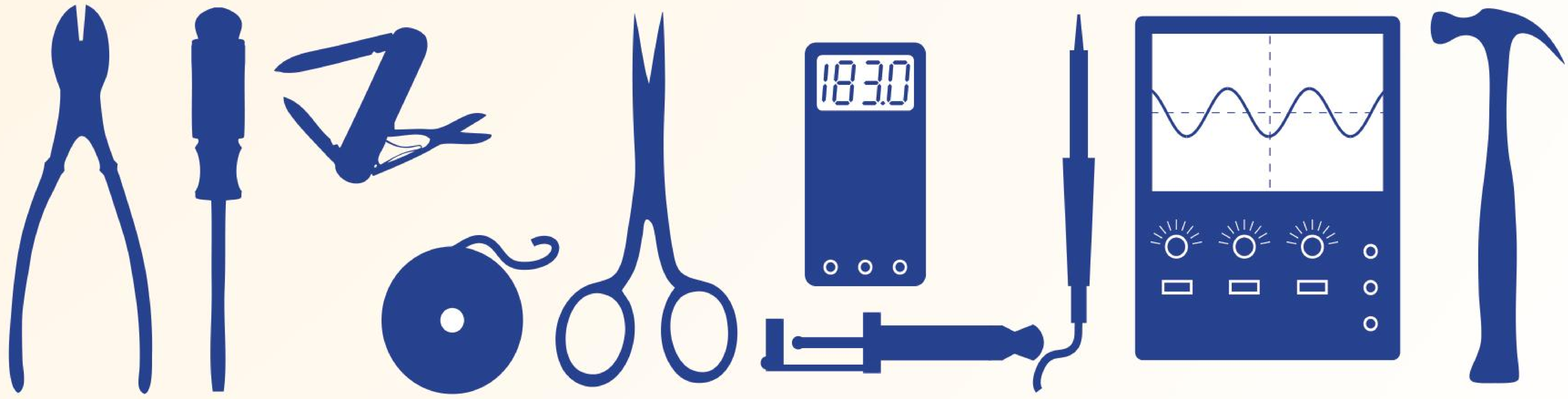


Fig.2. A small electric soldering iron such as the 15W type shown here (top) is needed for electronic project construction. As we all make mistakes, a desoldering pump / 'solder sucker' (bottom) is a prudent buy



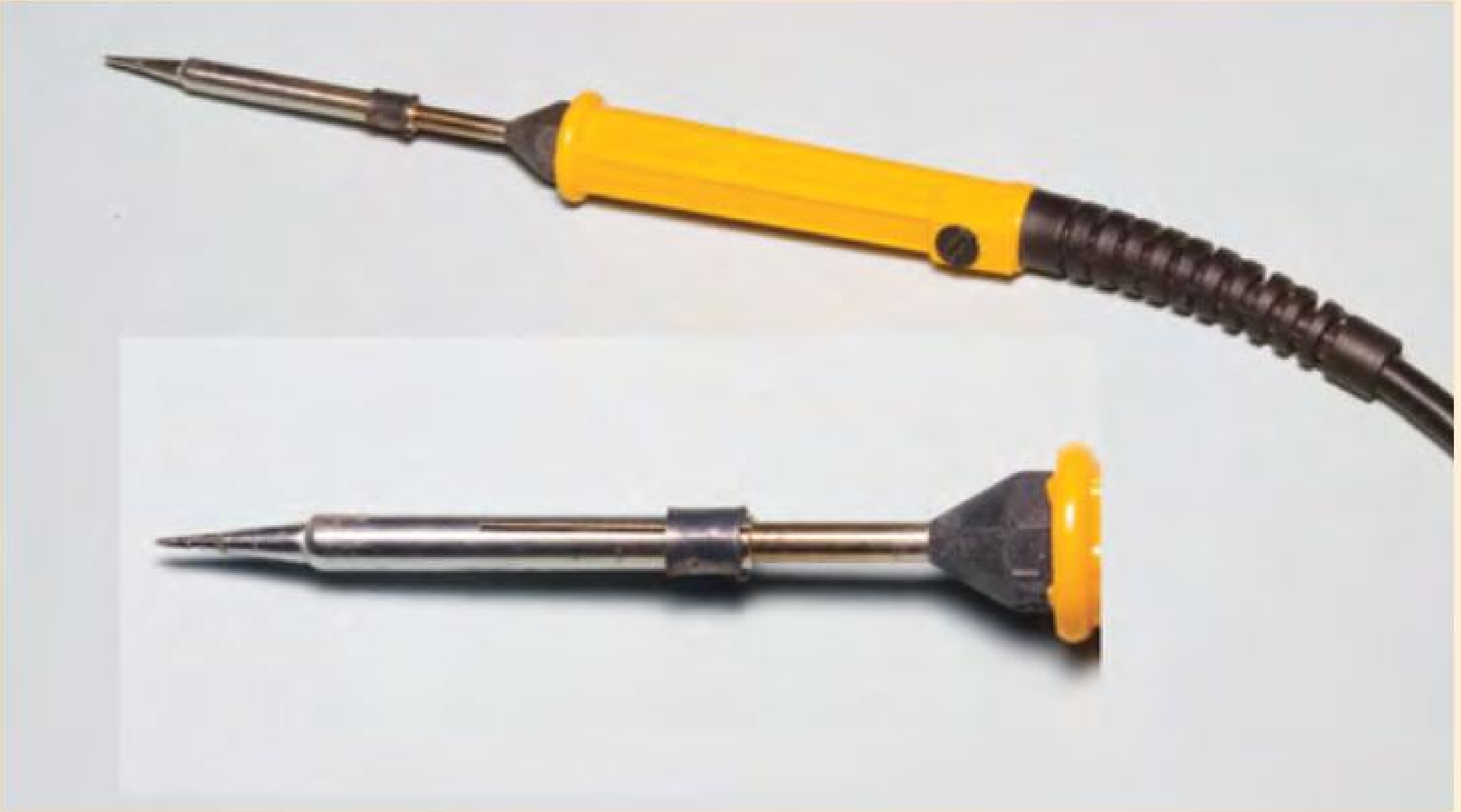


Fig.3. A low-power (12W) iron such as this one is ideal for working on intricate circuit boards, but not much else. Its 0.5mm-diameter bit virtually comes to a point

kits available that consist of an iron plus bit, a stand, some solder to get you started, and a soldering guide. One of these provides an easy way to begin, and is likely to be cheaper than buying everything separately. Such is the intricacy of modern circuit boards, that I often use a 12W iron having a 0.5mm-diameter bit (Fig.3). The drawback of such an iron is that it is not designed to handle anything other than intricate work, and it is not suitable for larger joints. Most irons have a range of interchangeable bits available, and it might be worthwhile having something like a 0.5 or 1mm-diameter bit in addition to the larger one supplied with the iron.

Ideally, we would get everything right first time, but in the real world a desoldering tool (Fig.2 bottom) is something that will probably be needed sooner rather than later. A variety of desoldering equipment is available, but practical experience suggests that a desoldering pump is the only inexpensive gadget that will provide fast and very effective results. A soldering iron is used to melt the solder, and the spring powered pump is then used to suck the molten solder from joint. Provided the accumulated bits of solder inside the pump are periodically removed, one of these tools should work well for many years.

Tweezers and loupes or magnifying glasses used to be useful tools for those of us who were 'not as young as you used to be'. With the ever-decreasing size of components and the tiny markings on them, I think that most project builders would find these to be more than a little useful. Practically any small tweezers will do, but metal ones (Fig.4) are generally better than the plastic type. A magnifying glass can be very helpful, but an 8X or 10X magnifying loupe is often better, especially when searching for short-circuits on circuit boards or trying to read minute lettering on miniature components. Loupes can be obtained from some craft and hobbyist tool suppliers, from photography shops, and of course on eBay.

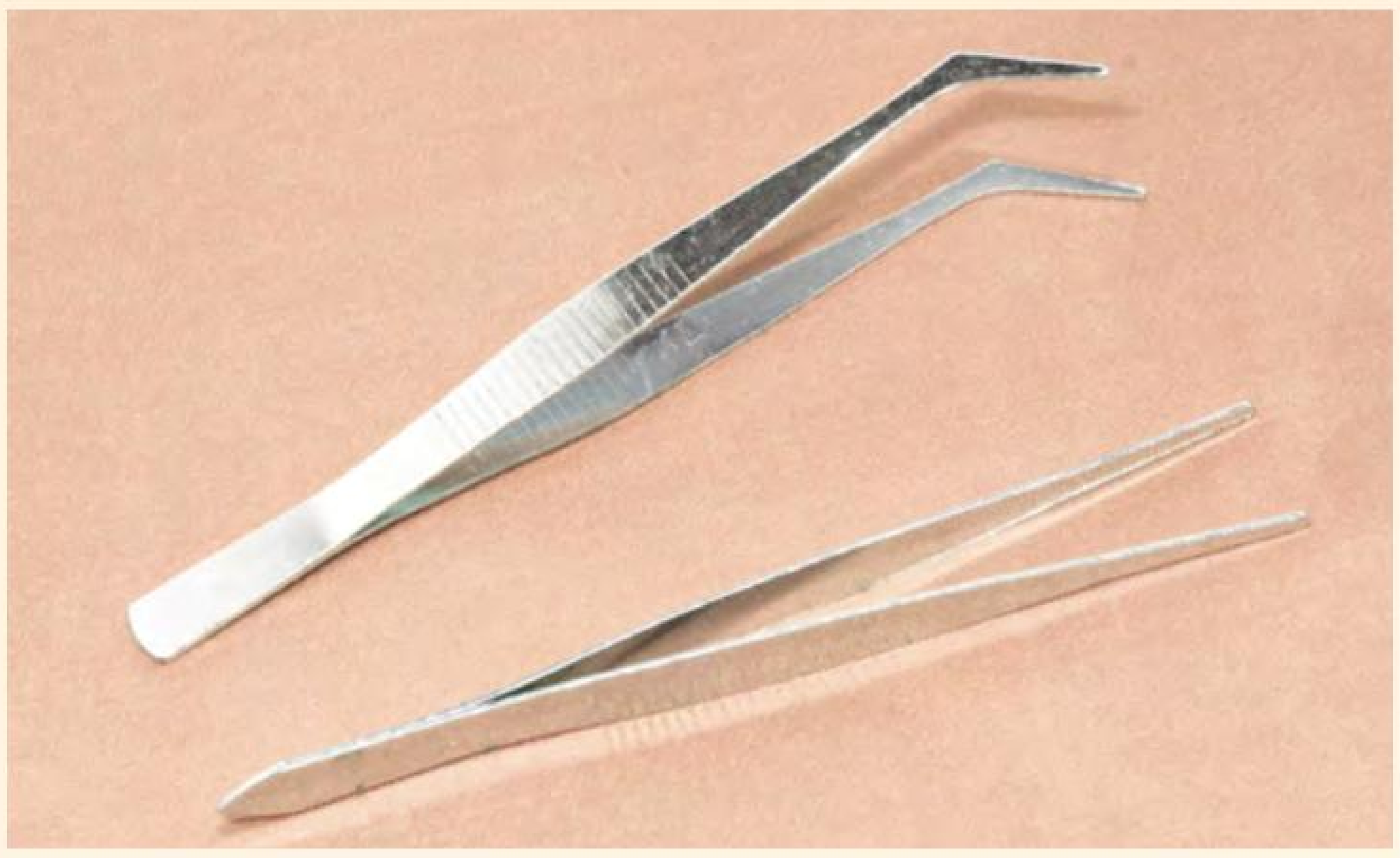


Fig.4. Tweezers are very helpful when dealing with modern miniature components. The angled type (top) are particularly useful

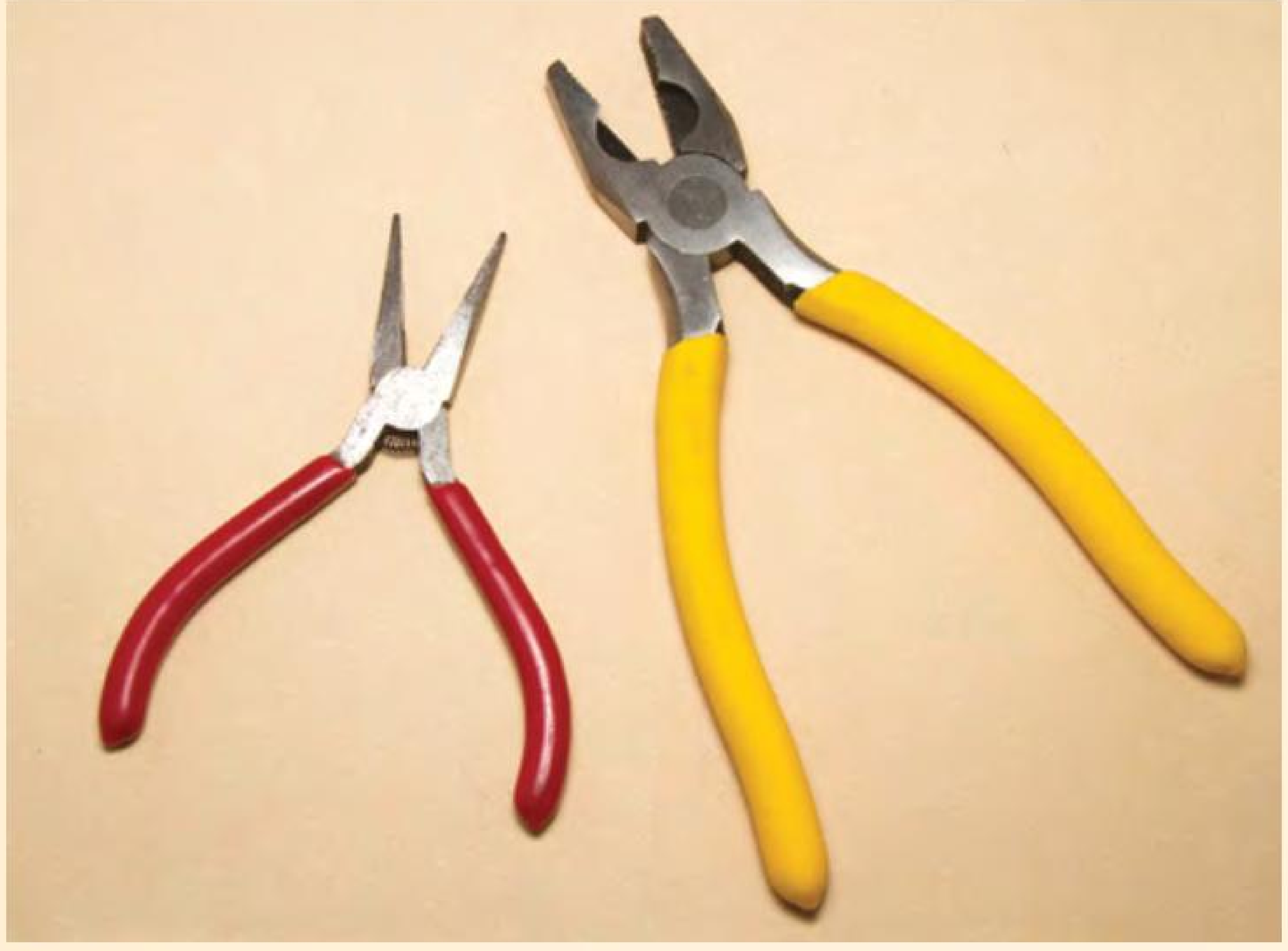


Fig.5. Large pliers such as the ones on the right are likely to be very useful, but for modern diminutive projects the small long-nosed type (left) are often more apposite

Getting to grips

A pair of pliers is something that will already be present in many households, but they will not necessarily be of a type that is well suited to electronic project construction. Electricians' pliers and the small long-nosed type (Fig.5) are likely to be the most useful in the current context. One or two files will also be very useful, especially a set of miniature files when working on cases. They can be used to make rectangular and other non-circular mounting holes, and can be used to 'fine-tune' any cut-outs where some fettling is required.

In a similar vein, most households are equipped with a few screwdrivers, but they will probably be too large for electrical use. Some small electricians' screwdrivers will be needed, as will wire cutters and insulation strippers. Wire cutters and strippers can be obtained as separate tools, but an inexpensive combined cutter and stripper tool will do for a start. Do not improvise with scissors, penknives, and the like, as this is likely to damage the tools and will probably not do a very good job. Plus, you risk harming yourself!

A drill of some kind and some drill bits are also standard household items. In days gone by you could get by with three or four drill bits of certain sizes. This is no longer the case though, and a full range of HSS (high-speed steel) drill bits from about 2.5 to 10mm in diameter is ideal. A large power drill will do, but a small cordless power drill or perhaps even a hand drill is often a better tool for the job. Project cases are often made from relatively soft materials such as plastic or aluminium, and they are often quite small. Precision and controllability are more important than power in this application.

Zap-free

It is important to realise that many modern semiconductors, and particularly the more expensive ones, are vulnerable to damage from static charges in the environment. Zapping components does not necessarily require large discharges complete with sparks and 'clicks'. Damage can be caused by relatively small static charges that give no obvious clues to their existence. Not all semiconductors are vulnerable to small static charges, but if in doubt, always assume that a semiconductor is one that is vulnerable to this type of damage.

A vast amount of anti-static equipment is available, but much of it is too expensive for occasional home use. It is advisable to obtain an earthed wrist band before building anything that uses expensive semiconductors. These wrist bands are quite cheap, and are available from electronic component suppliers. They can also be obtained from shops that sell computer parts. When wearing one of these, any static charge in your body is quickly leaked away to earth. If you regularly build electronic gadgets, it is also worth obtaining an inexpensive earthed mat for the work area.

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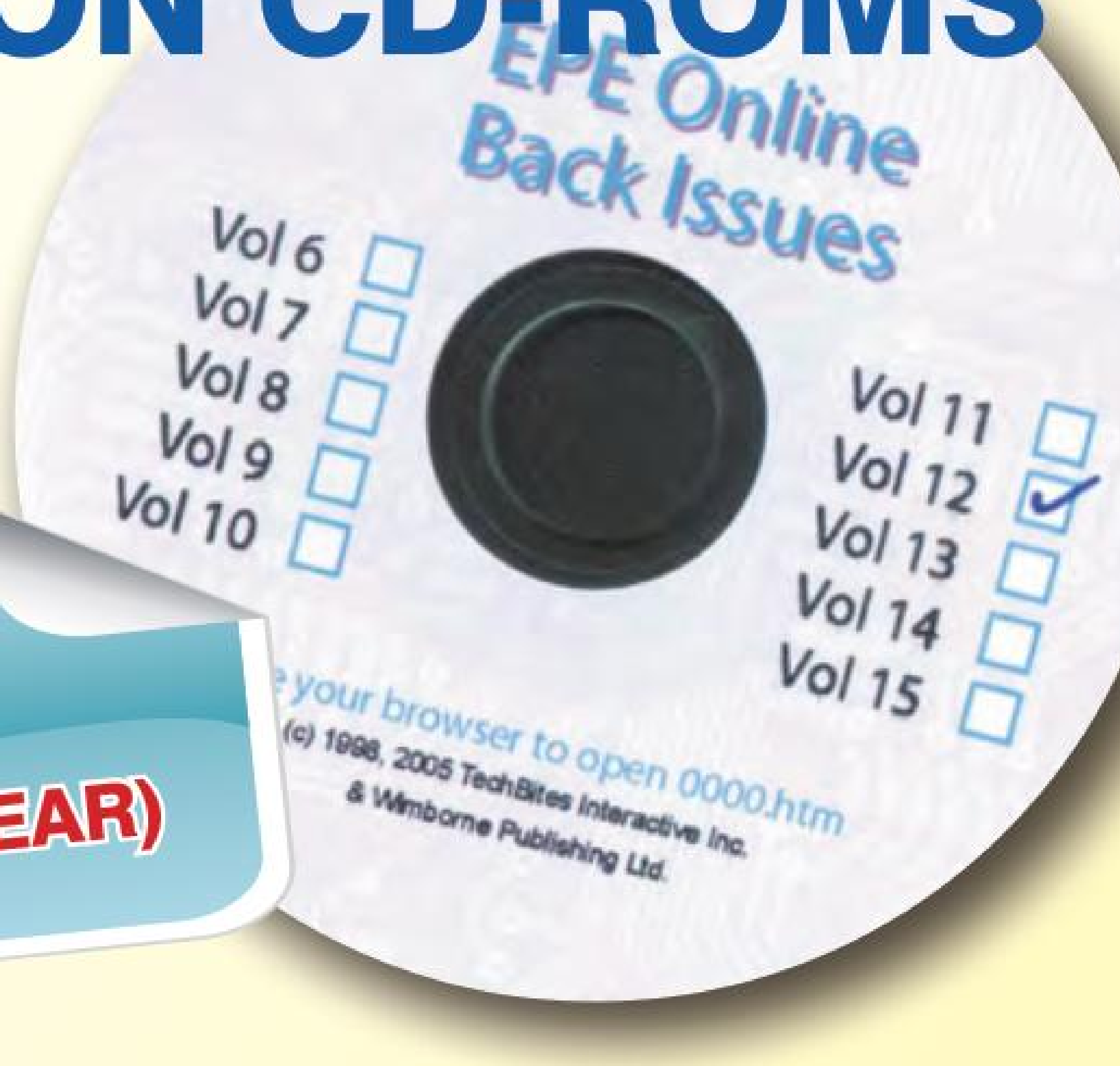
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VOL 25: BACK ISSUES – January 2011 to June 2011
VOL 26: BACK ISSUES – July 2011 to December 2011
VOL 27: BACK ISSUES – January 2012 to June 2012
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VOL 29: BACK ISSUES – January 2013 to June 2013
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All volumes include the *EPE Online* content of every listed issue. **Please note that we are unable to answer technical queries or provide data on articles that are more than five years old. Please also ensure that all components are still available before commencing construction of a project from a back issue.**

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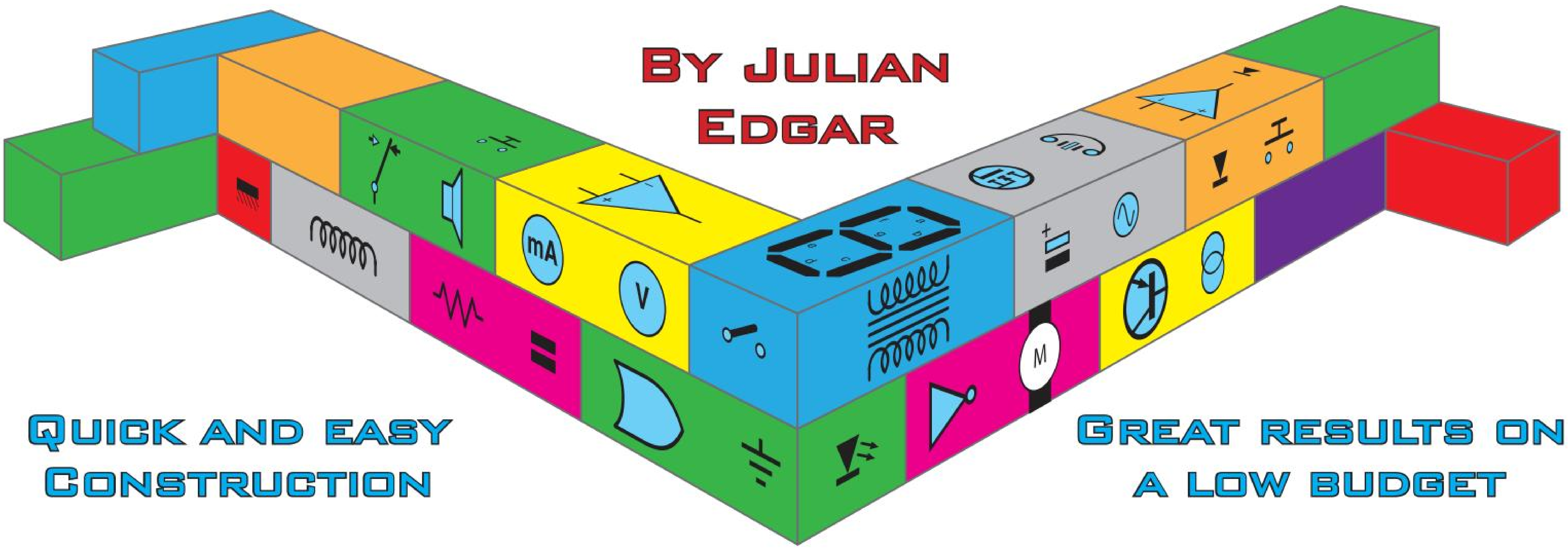

BY JULIAN EDGAR

QUICK AND EASY CONSTRUCTION

GREAT RESULTS ON A LOW BUDGET

PHONE BLASTER AUDIO

Large complex projects are fun, but they take time and can be expensive. Sometimes you just want a quick result at low cost. That's where this series of *Electronic Building Blocks* fits in. We use 'cheap as chips' components bought online to get you where you want to be... FAST! These projects range from around £15 to under a fiver... bargains!

This project came from a requirement that nothing off the shelf could quite match. We live in country Australia, only about 50 miles from Canberra – Australia's capital – but still in the land of kangaroos, lots of sheep farms, and a school bus that takes well over an hour to get my 11-year-old son, Alexander, to the school at the local biggest town. To while away the time, he reads books, reads (and plays games) on his tablet, watches the kangaroos and the kookaburras and the rabbits – and also, at times, wants to play music from his phone… and Adam, the bus driver, is fine with some music.

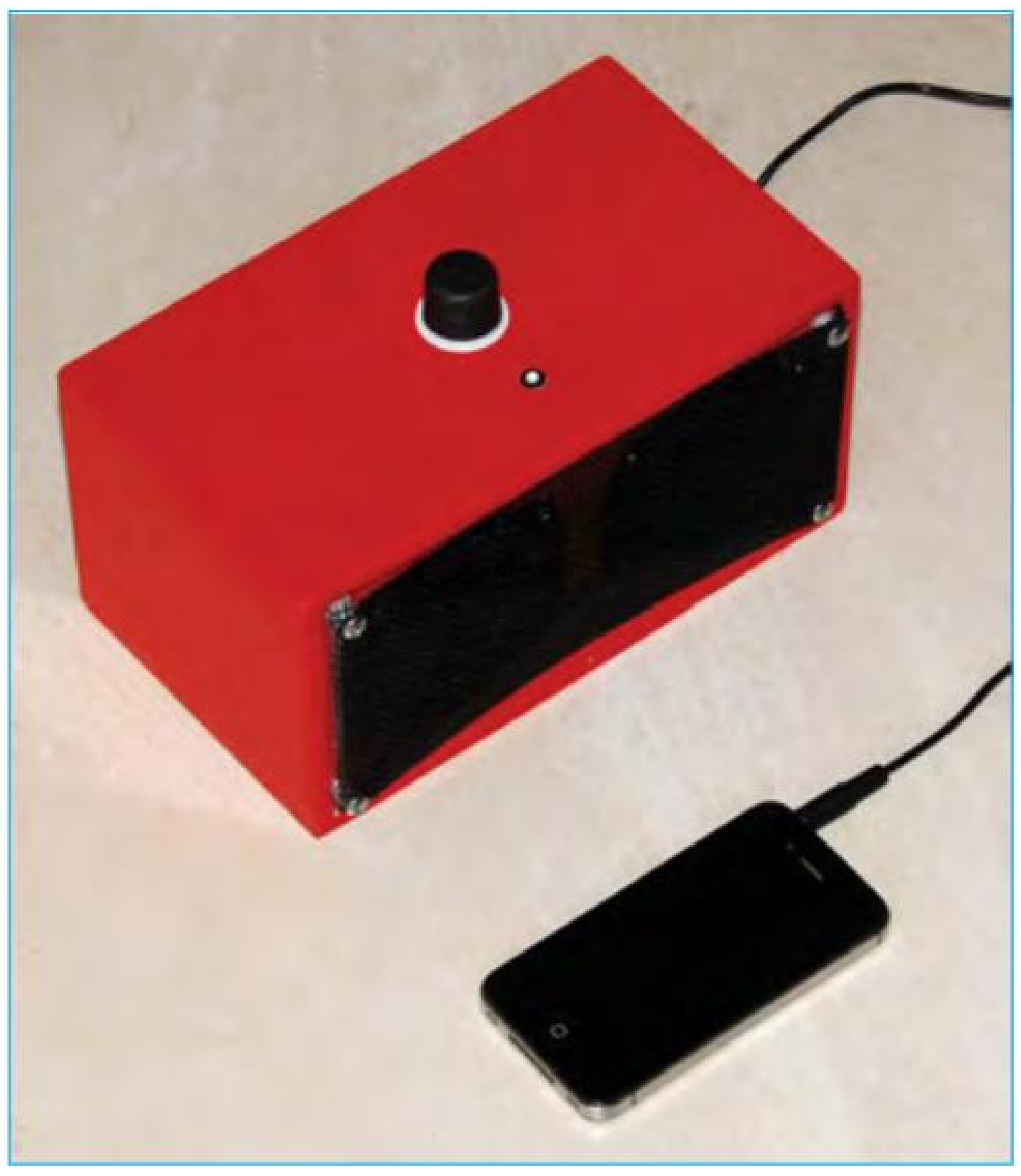

Fig.1. This stereo, amplified speaker system has excellent sound and yet is cheap and easy to make. It's ideal working with a phone, as here. Seen on the top panel is the rotary on/off switch and a 'power on' LED.

But how to amplify the music from the phone, in a device that can also be carried in a school bag all day? Sure, there's a myriad of amplified speakers around, but is there a set that is compact, sounds reasonably good – and can satisfy the 'bus cred' that the statement "My Dad made this!" satisfies? Not really, so I set to work.

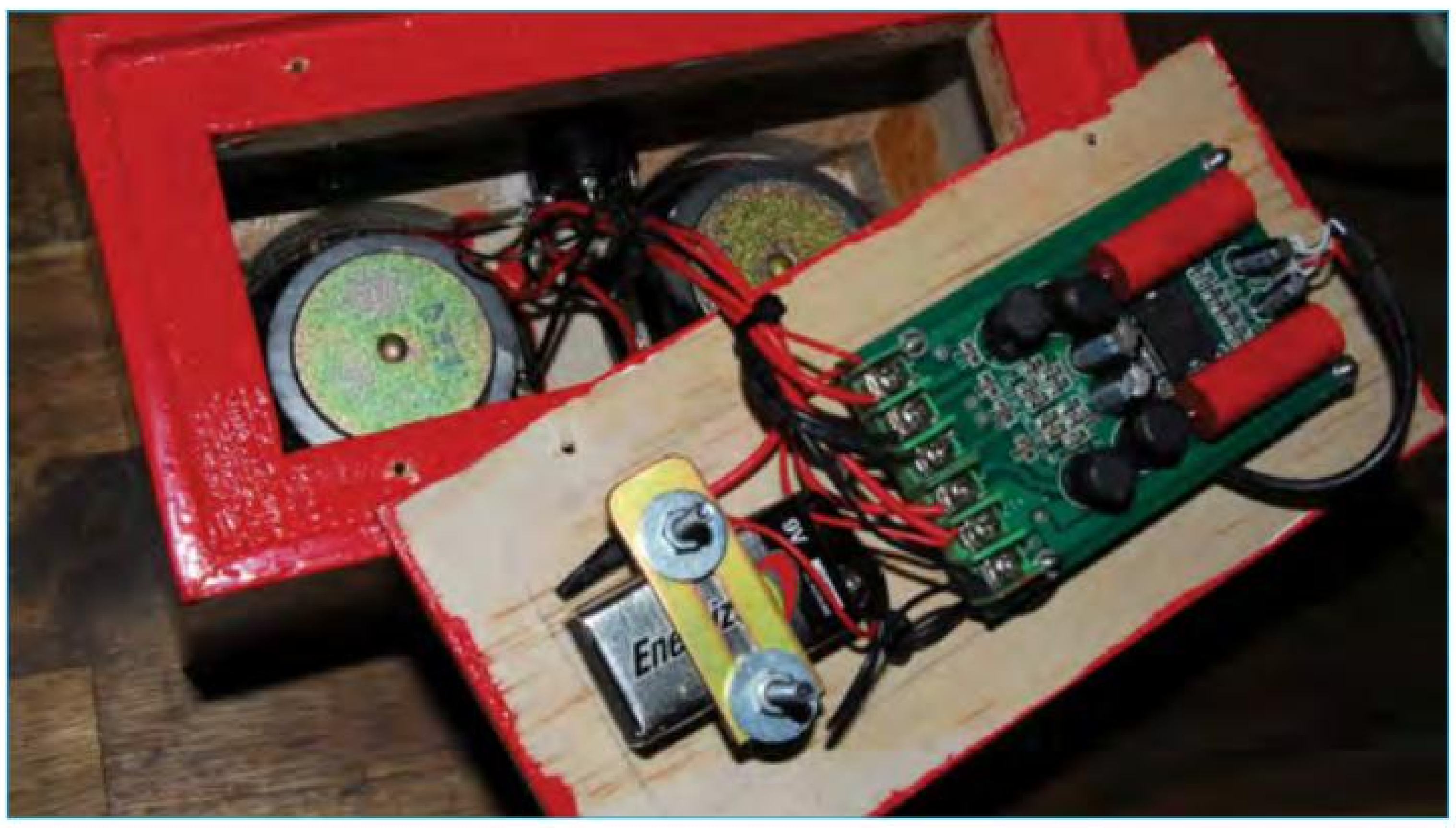

Fig.2. Two 3-inch speaker salvaged from a defective home iPhone sound system are used, along with a cheap but very effective prebuilt amplifier module. The system is shown here powered by a single 9V battery.

Enclosure

The starting point was marine-quality plywood, 7mm in thickness. This material formed the walls of the speaker enclosure. The front and back panels (also in 7mm marine ply) are attached to 18 × 18mm timber cleats that run around the inside of the enclosure. The outside dimensions of the enclosure are 210 × 110 × 120mm (w × h × d).

I mitred all of the corners, although butt joints would have perfectly adequate. Marine ply (as opposed to normal plywood) was used to give as much stiffness as possible to the enclosure, while keeping it light.

The enclosure was sized so as to just fit in a stereo pair of 3-inch speakers – the enclosure has an internal volume of about 1.2 litres. The speakers were salvaged from a discarded home-style iPhone amplified speaker system. They have large magnets and flexible roll surrounds. I could have developed a custom ported enclosure for these drivers, but measuring the Thiele-Small parameters of unknown speakers (while quite possible) is a lot of work that can be avoided if you're prepared to have some trade-off in ultimate low-frequency response by using a sealed enclosure.

Amplifier

The amplifier is the very low cost module that we covered in the October 2015 issue of *EPE*. In this application, its benefits are that is cheap, can work down to 7V, is efficient and fairly powerful. The amplifier is mounted on the inside of the rear panel, along with a 9V battery. The amplifier is available from eBay for around £4 – search under 'Tripath TA2024 amplifier module'.

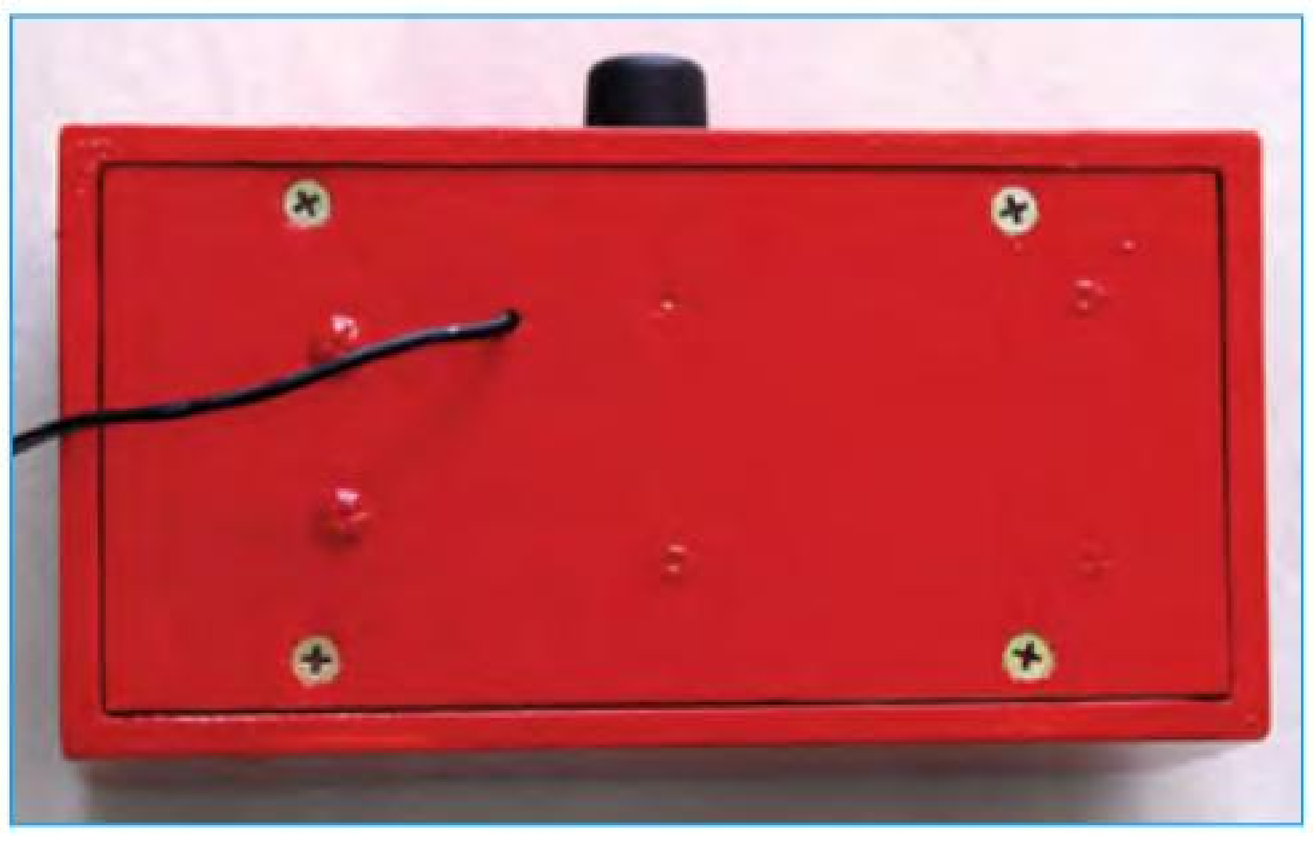

Fig.4. The rear panel shows the input cable and four screws that allow the back to be removed for battery replacement.

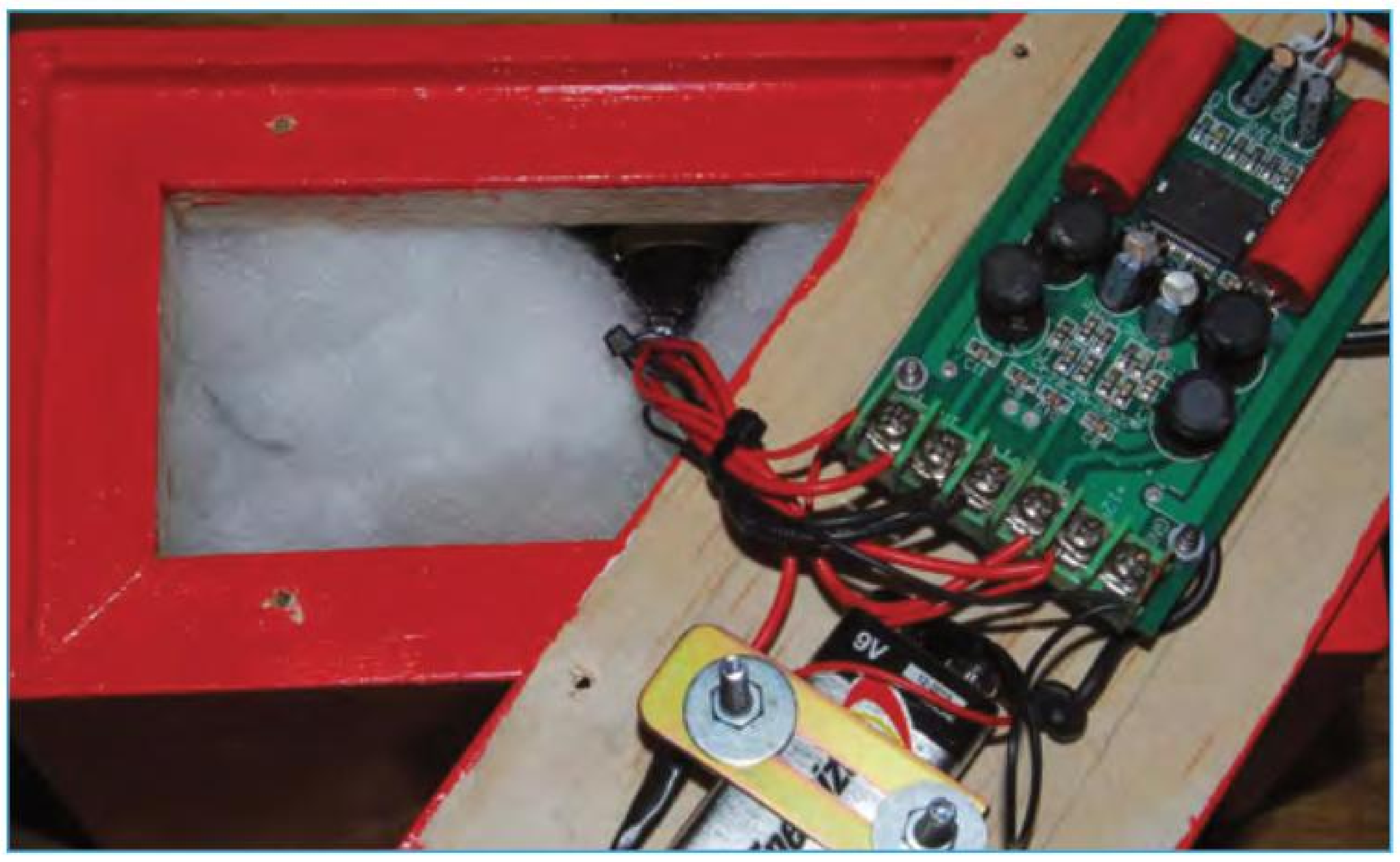

Fig.3. The inside of the sealed enclosure is packed with quilt wadding – very effective at improving the sound.

Details

The speakers are mounted through the front panel, with the panel itself glued and nailed into position. The rear panel is removable, mounting on its inside the amplifier module and the 9V battery. Through a side panel is mounted a rotary on/off switch (rotary, so it's less likely to be bumped inside a school bag) and a blue LED used as a 'power on' indicator. (I used an LED pre-wired for 12V.)

Inside the enclosure is placed a generous amount of acrylic quilt wadding, serving the dual purpose of preventing acoustic reflections through the cones, and acting to increase the effective volume of the enclosure. Across the front is placed a stiff metal grille, protecting the fragile cones from fingers and odd missiles located in school bags (and school buses).

The audio signal is fed to the board via a cut-off 1/8-inch stereo adaptor cord (the cheapest way of getting a pre-wired plug), with the cord protected against pull-out by a knot.

Some wood primer and red enamel finished the box with the required flair.

Absolutely fabulous!

And how does it sound? To be honest, I think it sound fabulous – far better than I'd expected. Some of that is just luck – the small drivers turning out to be good ones – but the stiff enclosure and decent amplifier module also play a big part.

When the system's frequency response is measured (using a free frequency generator app for the iPhone) the response is audible to just below 100Hz and Alexander can hear the output at 15kHz. (I'm too old to have a good high frequency hearing ability!) Admittedly, there are a few minor resonant peaks and humps along the way, but it still sounds better than all but the most high-end of small and portable amplified speakers.

So it's good enough to be also used as a picnic sound system, let alone entertain a bus-load of kids!

Battery life?

So, with a 9V battery, how long will the battery last? Well, that depends on how loud the system is played. I measured an 80mA current draw at a 'moderate' listening volume. That would make the 9V alkaline battery last something like six hours. Used 20 or 30 minutes a day, that should give reasonable battery life.

However, using a rechargeable battery (eg, an 11.1 lithium-polymer pack and associated charger) would be a better bet if the system is to be played a lot.

Next month

Next month, we'll get to grips with a handy new building block, a *Variable Frequency Module*. It's a pre-built item that has adjustable frequency, adjustable duty cycle – and can directly drive loads like high intensity LEDs and piezo buzzers. So don't miss the next super *Electronic Building Block* article!

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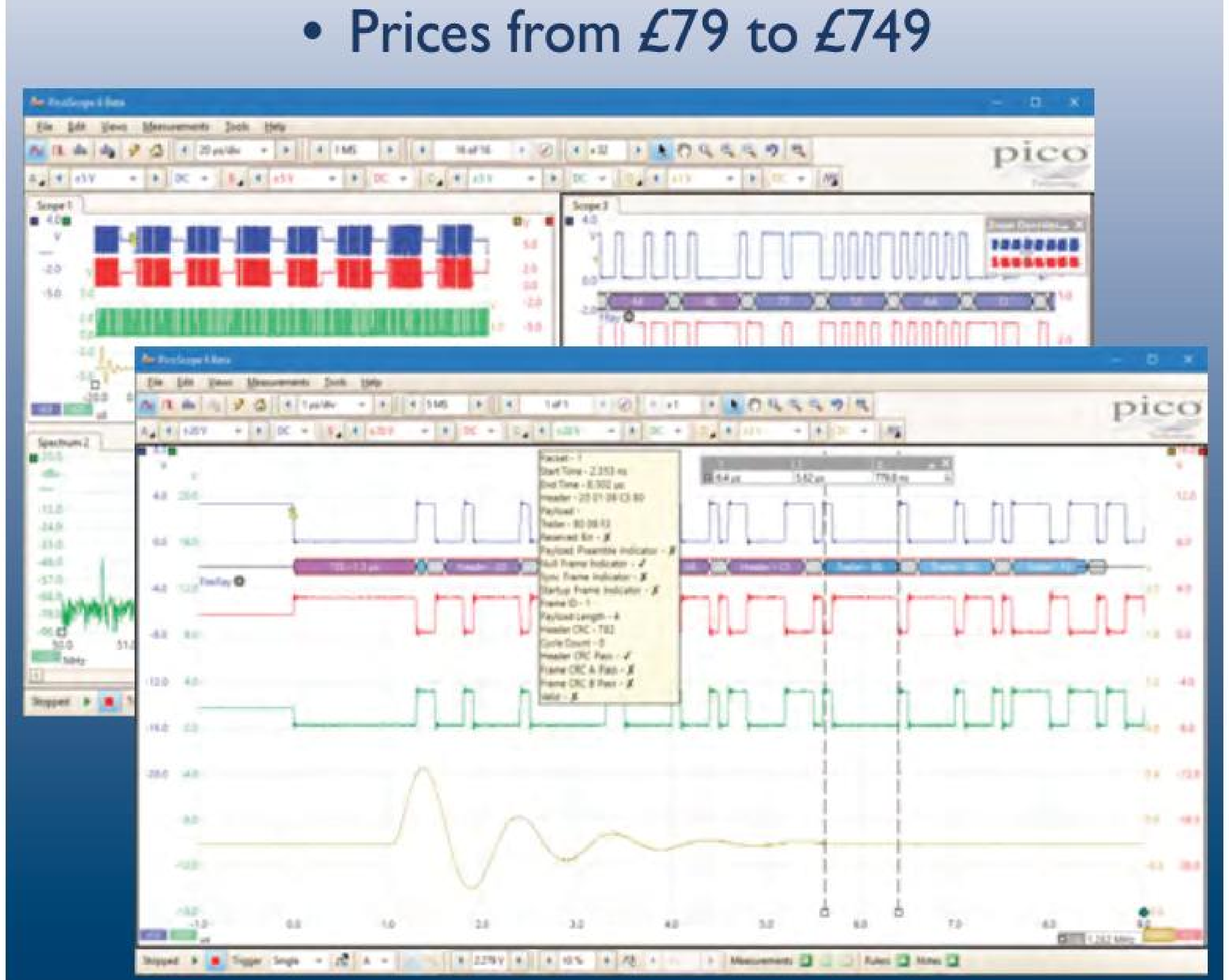

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Basic printed circuit boards for most recent *EPE* constructional projects are available from the *PCB Service*, see list. These are fabricated in glass fibre, and are drilled and roller tinned, but all holes are a standard size. They are not silk-screened, nor do they have solder resist. Double-sided boards are **NOT plated through hole** and will require 'vias' and some components soldering to both sides. **NOTE: PCBs from the July 2013 issue with eight digit codes** have silk screen overlays and, where applicable, are double-sided, plated through-hole, with solder masks, they are similar to the photos in the relevent project articles.

All prices include VAT and postage and packing. Add £2 per board for airmail outside of Europe. Remittances should be sent to **The PCB Service, Everyday Practical Electronics, Wimborne Publishing Ltd., 113 Lynwood Drive, Merley, Wimborne, Dorset BH21 1UU. Tel: 01202 880299; Fax 01202 843233; Email: orders@epemag.wimborne.co.uk. On-line Shop: www.epemag.com**. Cheques should be crossed and made payable to *Everyday Practical Electronics* **(Payment in £ sterling only)**.

NOTE: While 95% of our boards are held in stock and are dispatched within seven days of receipt of order, please allow a maximum of 28 days for delivery – overseas readers allow extra if ordered by surface mail.

Back numbers or photocopies of articles are available if required – see the Back Issues page for details. WE DO NOT SUPPLY KITS OR COMPONENTS FOR OUR PROJECTS.

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EPE SOFTWARE

Where available, software programs for *EPE* Projects can be downloaded free from the Library on our website, accessible via our home page at:
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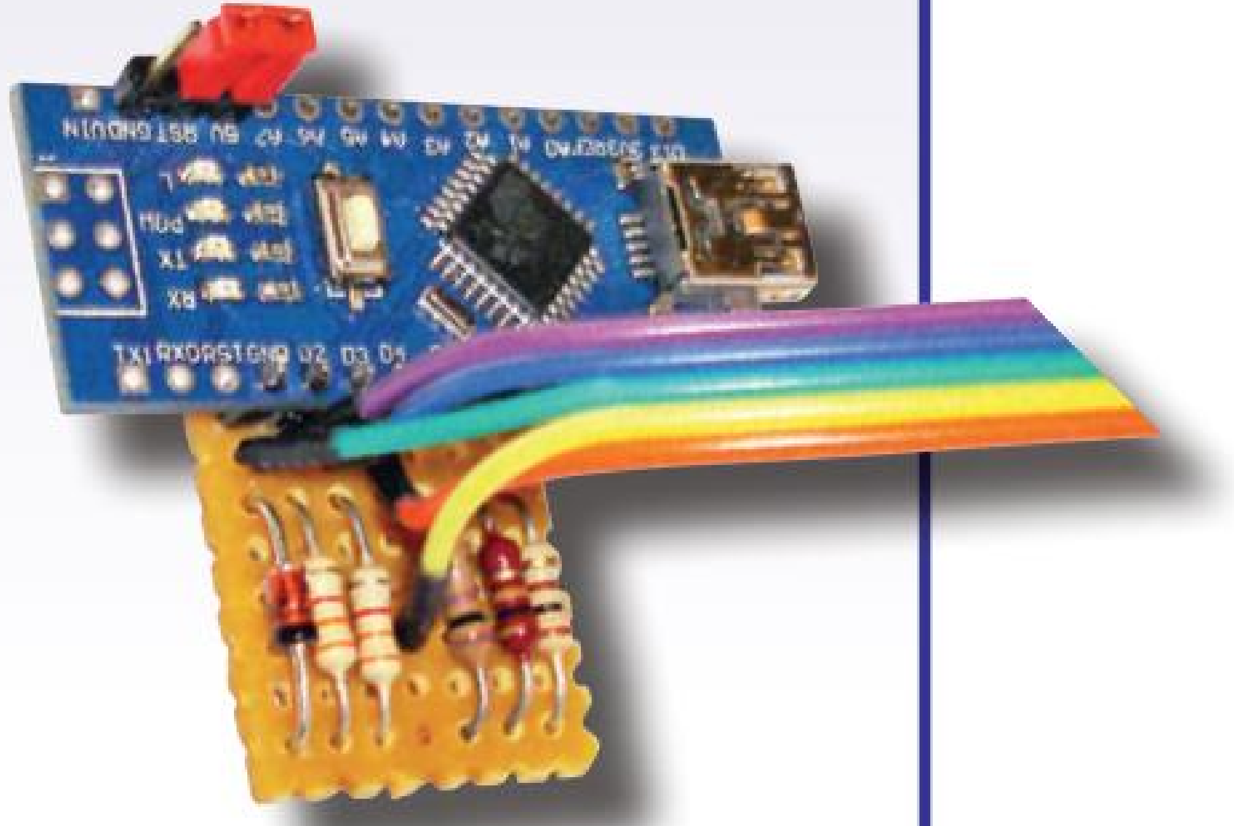
Next Month

Content may be subject to change

Fingerprint Access Controller

Do you hate carrying keys? So do we! Would you like to open your front door, security gate or your garage door with your finger? Now you can! This project comprises a fingerprint scanner (FPS), a two-row LCD and an electric door strike, all controlled by a PIC16F88 microcontroller.



Cheap programmer for the PIC32 microcontroller

Want to build a project that uses a PIC32? Great... but the prospect of programming a PIC32 can initially seem daunting. This minimal programmer will upload firmware into a PIC32 quickly and simply at very low cost.

Compact Hybrid Switchmode 100W Bench Supply – Part 3

In the third and final instalment of this elegant and flexible power supply project we complete the construction and discuss applications.

Teach-In 2016 – Part 10

In next month's *Teach-In 2016*, *Arduino World* will look at ultrasonic sensors. *Arduino Workshop* will introduce you to the practical aspects of object proximity and distance sensing. Our programming feature, *Coding Quickstart*, investigates the ultrasonic library and our *Get Real* project will describe the design and construction of a proximity warning system based on the Arduino and a low-cost ultrasonic transmitter/receiver module.

PLUS!

All your favourite regular columns from *Audio Out* and *Circuit Surgery* to *Electronic Building Blocks*, *PIC n' Mix* and *Net Work*.

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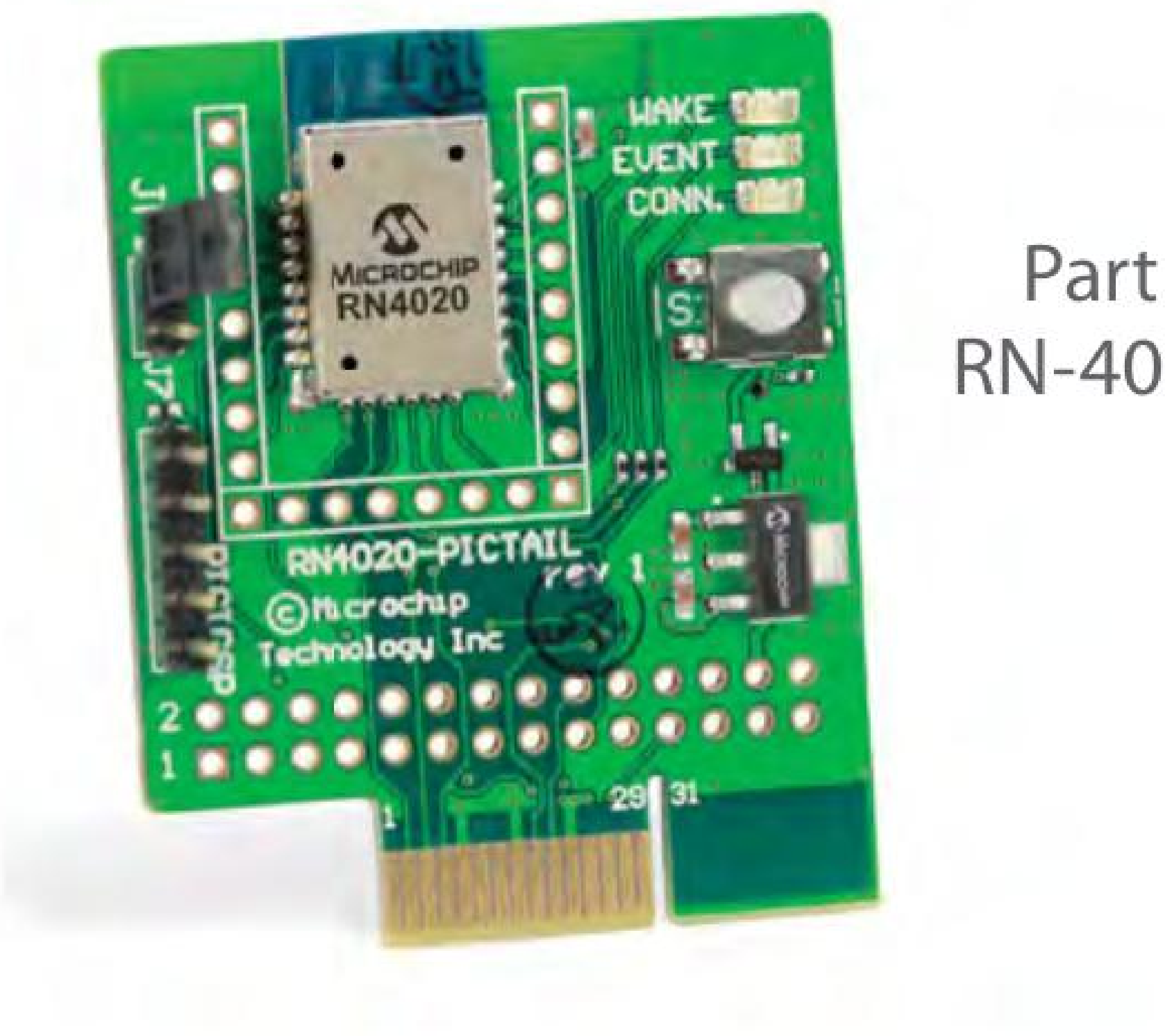
Development Tool of the Month!

RN4020 Bluetooth Low Energy PICtail™/PICtail™ Plus



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